ABSTRACT

Title of Thesis: MECHANISMS FOR TRAJECTORY OPTIONS ALLOCATION IN COLLABORATIVE AIR TRAFFIC FLOW MANAGEMENT

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Flight delays are primarily due to traffic imbalances caused by the demand for airspace resource exceeding its capacity. The capacity restriction might be due to inclement weather, an overloaded air traffic sector, or an airspace restriction. The Federal Aviation Administration (FAA), the organization responsible for air traffic control and management in the USA, has developed several tools known as Traffic Management Initiatives (TMI) to bring the demand into compliance with the capacity constraints. Collaborative Trajectory Option Program (CTOP) is one such tool that has been developed by the FAA to mitigate the delay experienced by flights. Operating under a Collaborative Decision Making (CDM) environment, CTOP is considered as the next step into the future of air traffic management by the FAA. The advantages of CTOP over the traditional the TMIs are unequivocal. The concerns about the allocation scheme used in the CTOP and treatment of flights from the flight operators/airlines have limited its usage. This research was motivated by the high ground delays that were experienced by flights and how the rerouting decisions were

made in the current allocation method used in a CTOP. We have proposed four alternative approaches in this thesis, which incorporated priority of flights by the respective flight operator, aimed at not merely reducing an individual flight operator's delay but also the total delay incurred to the system. We developed a test case scenario to compare the performances of the four proposed allocation methods against one another and with the present allocation mechanism of CTOP.

MECHANISMS FOR ALLOCATION OF CONSTRAINED AIRSPACE RESOURCES AND REROUTING DECISIONS IN A COLLABORATIVE TRAJECTORY OPTIONS SET

by

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List of Abbreviations

NAS – National Airspace System (USA)

US – United States of America

BTS – Bureau of Transportation Statistics

USDOT – United States of America Department of Transportation

ATCSCC – Air Traffic Control System Command Center

TFR – Temporary Flight Restrictions

TMI –Traffic Management Initiatives

GDP –Ground Delay Program

AFP – Airspace Flow Program

GS – Ground Stop

MIT – Miles-in-Trail

CDM – Collaborative Decision Making

ATFM – Air Traffic Flow Management

ANSP – Air Navigation Service Providers

FCA – Flow Constrained Area

SEVEN – System Enhancement for Versatile Electronic Negotiation

CTOP – Collaborative Trajectory Options Program

RTC – Relative Trajectory Cost

FCFS – First Come First Served

ACID – Aircraft Identification Number

IGDT – Initial Gate Departure Time

ERDT – Earliest Runway Departure Time

GDE – Ground Delay Equivalent

RMNT – Required Minimum Notification Time

TVST – Trajectory Valid Start Time

TVET – Trajectory Valid End Time

ALT – Altitude

SPD –Speed

IAT – Initial Arrival Time

BPRA – Balanced Priority Resource Allocation

RIBPRA – Reroute Incentive Balanced Priority Allocation

RIBPRA_E – Modified Reroute Incentive Balanced Priority Allocation

RIBPRA_RBS – Reroute Incentive Balanced Priority Allocation based on RBS

ZID – Indianapolis Air Route Traffic Control Center

ZOB – Cleveland Air Route Traffic Control Center

ZDC – Washington Air Route Traffic Control Center

ZNY – New York Air Route Traffic Control Center

ZBW – Boston Air Route Traffic Control Center

ICAO – International Civil Aviation Organization

Chapter 1: Introduction

Aviation operations are supported by one of the most complex transportation systems in the world. The complex nature of the system is attributed to the number of aircraft, extensive network of airports, number of passengers, complexity in quantifying the airspace volume, safety concerns, and the number of controlling entities, which makes scheduling of the aircraft of profound importance. The determination of the National Airspace System (NAS) capacity is complex. NAS capacity depends on many factors, such as meteorological conditions, passenger demand, socio-economic trend information (changes in demographics, income, market power, and other factors), airport capacity, and fleet mix (Ball et al., 2007). The numerous factors in estimating the NAS capacity and large variations in performance and efficiency lead to large uncertainty in the aviation environment.

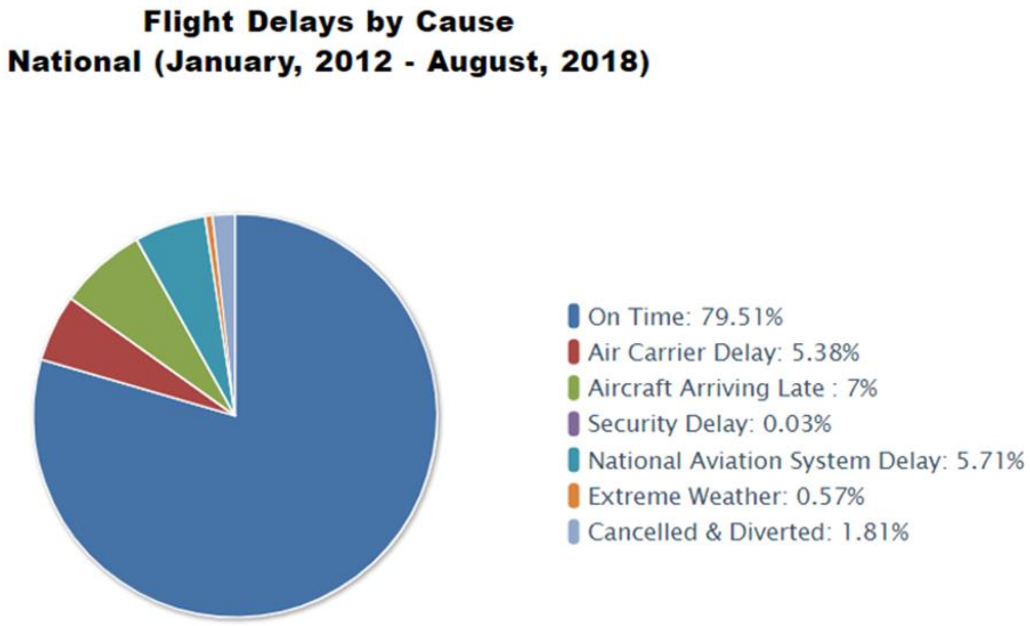


Figure 1: On-time Arrival Performance National (BTS USDOT, 2018)

Flight delays are primarily a result of the traffic imbalance caused by the demand for airspace resources exceeding its capacity. From Figure 1, it is easy to see that one in five US airline flights arrived at its destination over 15 minutes late and from Figure 2, about a third of these late arrivals were a direct result of the inability of the NAS to handle the traffic demands that were placed upon it. Capacity reduction in the NAS occurs due to a wide number of reasons, including adverse weather conditions, an airspace restriction such as a Temporary Flight Restriction (TFR), or due to an overloaded air traffic control sector. The reason that demand exceeds capacity is a constraint of some kind. To bring the demand into compliance with the capacity constraints and mitigate the delays, the Federal Aviation Administration (FAA), the organization responsible for air traffic control and management in the USA, has created several tools known as Traffic Management Initiatives (TMI). Some of the main TMIs developed for this purpose are Ground Delay Program (GDP), Airspace Flow Program (AFP), Ground Stops (GS), and Miles-in-Trail (MIT). Despite the planning efforts and a wide range of TMIs developed by the FAA, the flights still experience delays because of the complex dynamic nature of the system and uncertainty involved in the flights' schedules. To further improve the performance of these TMIs, the FAA adopted Collaborative Decision Making (CDM). CDM is an operating paradigm, initiated by the FAA to improve Air Traffic Flow Management (ATFM) through increased collaboration between airspace users and Air Navigation Service Providers (ANSP). The functional goals of CDM are to create a better knowledge base and a common situational awareness by sharing information to both ANSP and the airspace users.

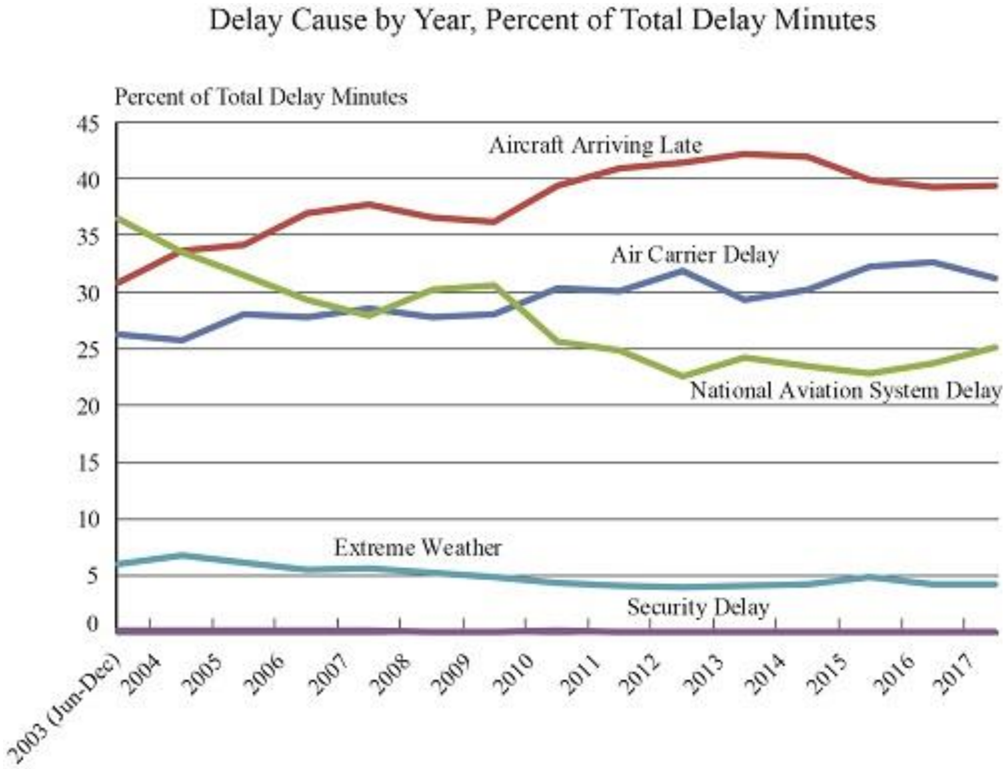


Figure 2: Delays Cause by Year, Percent of Total Delay Minutes (BTS USDOT, 2018)

TMIs like GDP and AFP have been incorporated under the CDM paradigm. A GDP is aimed at controlling arrivals into a capacitated NAS element by issuing delays to flights at their departure airports (ground delays) to avoid overloading the capacitated element i.e. airports. An AFP is designed similarly, but to control the traffic flow through a Flow Constrained Area (FCA); FCAs are geometric descriptions of the regions of constrained capacity. When an AFP assigns ground delays to flights that were scheduled to pass through an FCA, the flight operators are then given an option to either take the ground delay assigned or to reroute the flight around the FCA. In 2007, the FAA developed a new TMI tool under the CDM paradigm, allowing for more input and flexibility from flight operators in the way that constraints are handled. Initially, the new tool was known as System Enhancements for Versatile Electronic Negotiation (SEVEN). The program is now known as the Collaborative Trajectory Options Program (CTOP). CTOP is the natural progression of GDP and AFP under the CDM operating paradigm. CTOP combines the capabilities of GDPs and AFPs, and it issues ground delay and/or reroutes to flights to balance demand with capacity. However, in CTOP the reroutes are done collaboratively, unlike in an AFP. The decisions made are collaborative in the sense that CTOP allows flight operators to submit a set of desired route options known as Trajectory Options Set (TOS) and indicate an associated pre-calculated cost for each route (RTC). It then performs the allocation of the route options and ground delays to the affected flights so as to satisfy the flight operators' route preferences and FCA capacity constraints. The present version of CTOP performs the route and delay assignment using the Ration by Schedule (RBS) policy, which is based on the First Come First Served (FCFS) principle. We will be looking in detail about the allocation process in Chapter 4 of this thesis.

1.1. Literature review:

Air traffic management under the CDM operating paradigm has an extensive body of literature. However, there is only a limited list of literature available on the allocation process of CTOP. There have been a few heuristics allocation algorithms proposed for CTOP. Pourtaklo and Ball (2009) proposed a novel approach to allocating constrained airspace resources. The methods proposed were designed for AFPs and SEVEN (the initial name of CTOP). They described a new resource rationing principle and an alternative methodology for use in rationing access to constrained en route airspace. The proposed allocation mechanism falls into a category of methods designed for fair treatment of claimants to, and allocation of, a constrained resource. It involved determination of the fair share of the constrained resource for each flight operator based on the original flight schedule as the basis of fairness. The fairness metric, fair share, has been used in this thesis as an equity metric to compare the proposed allocation mechanisms. Flights were allocated slots consistent with the fair share determined. The methods explicitly allowed some flights to be refused access, since the flight operators retain the option of rerouting around the constrained airspace. The methods required information about preference of flights from the flight operators.

Vlachou and Lovell (2013) proposed a way for flight operators to express preference structure for their flights that are affected by CTOP and developed two resource allocation mechanisms build on the approaches proposed by Pourtaklo and Ball (2007) that improve the system efficiency and simultaneously take the flight operator preferences into account. The proposed preference structure was a replacement to the TOS, which strayed away from the framework of CTOP. They also do not solve the problem of accounting for flights that flight operators decide to reroute around an FCA. They also introduced a new system efficiency metric, preference weighted delay, which has been used in this thesis to compare the performance of the proposed allocation approaches.

Kim and Hansen (2013) proposed a modeling framework through which one can evaluate and compare en route resource allocation schemes, and investigate the issues involved with incorporating user inputs in allocating constrained capacity. They have specified four resource assignment schemes that feature different user preference inputs and allocation mechanisms. These schemes are designed to offer users flexibility and ease in providing general preference information, or clear incentives to make the effort required to develop and provide timelier and richer information.

There have been a few mixed integer linear models proposed as alternatives to the current CTOP resource allocation mechanism. Zhu and Wei (2018) proposed a mixed integer linear model to assign trajectory options and delays to the flights in a CTOP with the objective to minimize total system delay costs while maintaining equality across airspace. Rodionova et al. (2018) proposed an alternative scheduling approach based on linear optimization that differs from the current version of CTOP RBS allocation policy. They also developed a modified version of RBS, RBSall, which simultaneously considered constraints from multiple FCAs.

Murça (2018) developed a multi resource allocation model, a route and slot allocation model that incorporates a flight operator's disutility cost of rerouting to avoid an impacted airspace to optimally schedule flights into multiple FCAs. Murça also evaluated the benefits of CTOP and assessed the impacts of accounting for airline preferences on individual and aggregate system delays.

Jakobovits et al. (2007) described automated algorithms for applying restrictions to air traffic to prevent one or more sectors of airspace from becoming overloaded. They evaluate the merits of both heuristic and classical optimization approaches and identify tradeoff issues that affect the selection of an algorithm for the airspace problem.

Several models have been observed in the literature review; these could be broadly classified into heuristics algorithms and optimization. The airlines have shown a hesitance towards adopting an optimization model, because of concerns with the objective function of the model, and equity. Traffic management actions based on optimization models are the biggest form of uncertainty for the flight operators after uncertainties in capacity and demand due to weather forecasts. Optimization models also pose another concern of computational speed and granularity, as optimization models rely on the discretization of time. Space-based allocation models featured in Zhu and Wei (2018) and Rodionova et al. (2018) are hugely impacted by this. Additionally, with an increase in granularity, the level of detail in discretization of space and time adds to the computational burden.

The models in the literature most similar to our proposed models are models proposed by Pourtaklo and Ball (2009) and Vlachou and Lovell (2013). First, these models require the flight operator's flight preferences. Finally, these preferences are incorporated in the allocation mechanisms. There are several contrasting differences in which the preferences are expressed and restricted between those models and the ones proposed in this thesis. Additionally, in the models proposed by Pourtaklo and Ball (2009) and Vlachou and Lovell (2013), a slot is assigned to a flight operator by a random process based on the slots that are owed to the flight operator based on their schedule of flights at the FCA. The four allocation methods proposed in this thesis represent a combination of heuristics and greedy algorithms, but do not make any probabilistic assignments.

1.2. Organization:

This thesis is organized into 8 related chapters. Chapter 1 introduces the constrained airspace and its effects on flight, and the origin of CTOP. Chapter 2 describes CTOP in detail to understand its framework, and the inputs to the process. CTOP is a new TMI that is yet to be completely adopted by both the FAA and the flight operators; as result of this there is lack of an extensive list of real case studies and historical data sets available to understand the interactions between the flight operators and ANSP in a CTOP. In Chapter 3, we propose a model that could be used to represent the TOS for each flight, in the absence of real data from carriers. The developed cost functions were used to calculate the RTC for each trajectory option in a TOS. In this thesis, we propose four allocation approaches that could be used to perform route and delay assignment in a CTOP. The motivation behind these approaches was the room for improvement in the performance of the present allocation policy used in CTOP. We have used a simple stylized analytical model to show that there is room for improvement in the present form of CTOP in Chapter 4. The four proposed allocation approaches are explained in detail in Chapter 5. The proposed allocation approaches need an additional piece of information from the flight operators; this is the preference value among its own flights. The preference value reflects the relative priority of flights under the respective flight operator. We describe four strategies that could be employed by the flight operators to come up with the preference values in Chapter 6. Chapter 7 describes the test case scenario developed for the deterministic simulation. It also presents results from the test case scenario and metrics used to help compare the proposed allocation methods with the present CTOP allocation method and between the proposed allocation methods. Conclusions and future research needs are presented in Chapter 8.

Chapter 2: Collaborative Trajectory Options Program (CTOP):

This chapter builds on the brief introduction of CTOP provided in Section 1.1, to provide additional information about the CTOP TMI to understand the interactions and framework. CTOP is a new TMI tool developed to operate under the CDM paradigm, allowing for more input and flexibility from flight operators in the way that constraints are handled. CTOP combines the capabilities of GDPs and AFPs, and assigns delay and/or reroutes around one or more FCA-based airspace constraints to balance demand with available capacity (FAA, 2014). The decisions made are collaborative in the sense that CTOP allows flight operators to submit a set of desired route options known as Trajectory Options Set (TOS) and indicate an associated pre-calculated cost for each route (RTC). It then performs the allocation of the route options and ground delays to the affected flights so as to satisfy the flight operators' route preferences and FCA capacity constraints.

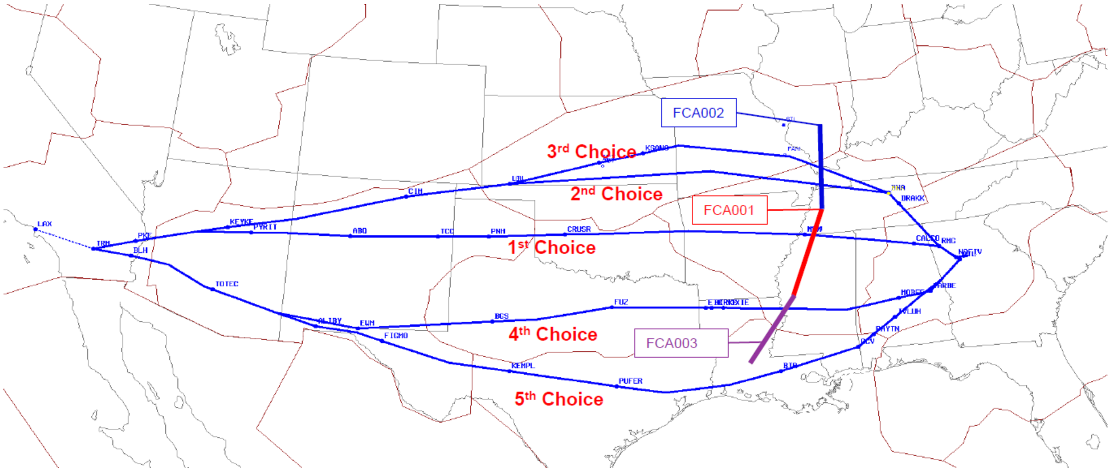
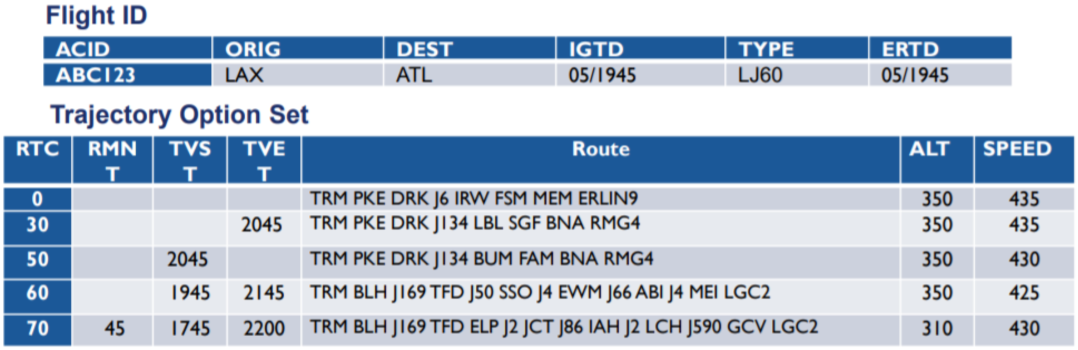


Figure 3: Flight Routes and FCAs (geometric description of the region of constrained capacity) (FAA, 2014)

The FAA creates a CTOP to restrict aircraft demand through a Flow Constrained Area (FCA) during a predetermined period. CTOPs are managed by the Air Traffic Control System Command Center (ATCSCC). The process for defining a CTOP begins with identification of a forecast or an actual constraint. The constraint is then translated into an FCA by the ATCSCC

(Figure 3). An FCA is a geometric description of the region of constrained capacity. Once the FCAs are defined by the ATCSCC, ATCSCC identifies the flights that are planned to fly through these FCAs as well as exempted flights. The exempted flights are usually the flights that are already in the air when the program is issued, international flights, and flights included in any higher priority TMI. The FCA's details and corresponding capacities are shared with the involved NAS users (flight operators).



Flight ID

ACID	ORIG	DEST	IGTD	TYPE	ERTD
ABC123	LAX	ATL	05/1945	LJ60	05/1945

Trajectory Option Set

RTC	RMNT	TVST	TVET	Route	ALT	SPEED
0				TRM PKE DRK J6 IRW FSM MEM ERLIN9	350	435
30			2045	TRM PKE DRK J134 LBL SGF BNA RMG4	350	435
50		2045		TRM PKE DRK J134 BUM FAM BNA RMG4	350	430
60		1945	2145	TRM BLH J169 TFD J50 SSO J4 EWM J66 ABI J4 MEI LGC2	350	425
70	45	1745	2200	TRM BLH J169 TFD ELP J2 JCT J86 IAH J2 LCH J590 GCV LGC2	310	430

Figure 4: TOS example of a flight from LAX (Los Angeles Airport) to ATL (Hartsfield-Jackson Atlanta Airport) (FAA, 2014)

ATCSCC receives the TOSs submitted by the flight operators for each of their affected flights and performs the allocation of the route options and departure delays to these flights to satisfy the option preferences and FCA capacity constraints following the Ration by Schedule (RBS) policy, the current allocation mechanism of CTOP. The current resource allocation mechanism of CTOP is explained in detail in Chapter 4. A TOS is a set of route options that the flight operators want to have considered by the CTOP allocation algorithm in assigning a route to a flight, either through or around an FCA. Figure 4 shows an example of a TOS for a hypothetical flight with Aircraft ID (ACID) ABC123, flying from Los Angeles (LAX) to Atlanta (ATL). The aircraft type is a Learjet 60 (LJ60). The Initial Gate Departure Time (IGDT) is 7:45 pm on the 5th of the month, as is the Earliest Runway Departure Time (ERDT). Each posited route option for that flight is assigned (by the carrier) the following information:

- Relative trajectory cost (RTC). This specifies the cost of this route relative to the planned/primary trajectory, expressed in terms of ground delay equivalent (GDE) minutes.
- Required minimum notification time (RMNT). This is the minimum notification that must be provided to the carrier in order for it to be able to enact this route option.
- Trajectory Valid Start Time (TVST)
- Trajectory Valid End Time (TVET). Together, the TVST and TVET give the time window during which this route option is acceptable to the carrier.
- Route. This is a sequence of NAS airspace elements, including fixes, jetways, corner-posts, etc., that define the physical trajectory.
- Altitude (ALT). This is expressed in units of 100s of feet.
- Speed (SPD). This is expressed in units of nautical miles per hour.

The CTOP allocation algorithm will calculate the adjusted cost for each route option in the TOS. The adjusted cost is the sum of the RTC and required ground delay for the candidate trajectory. In Chapter 3, we explain how these trajectory options in a TOS can be represented and how their respective RTC values can be calculated. Flight operators also have the option not to participate in the CTOP. Such cases arise when airlines are willing to simply accept whatever the ground delay is assigned on the primary/filed trajectory of the flight. In a sense, this is like the carrier choosing to revert to the disposition that would have been likely had a more traditional Ground Delay Program been applied as the TMI, instead of the more contemporary CTOP.

Chapter 3: Model for Trajectory Options Set Generation

CTOP is a new TMI that is yet to be fully enforced by the FAA and the flight operators. As a result of this there is to date no extensive list of real case studies and historical data sets available to understand the information exchanges between the flight operators and ANSP in a CTOP. A new concept in CTOP allows flight operator to submit a set of desired routes, TOS, and indicate a pre-calculated cost for each route. In reality, these TOSs would be generated by the flight operators/airlines. Real data would have been preferable, but there has not been enough experience yet with CTOP to generate a rich set of TOSs for different situations. In order to be able to test different allocation methods, we needed to generate a set of synthetic carrier TOSs. If one were to simulate a given situation, information like ACID, departure airport, arrival airport, IGTD, ERTD, RMNT, Aircraft Type, TVST, and TVET, which are all part of a TOS, could be generated from historical data unambiguously, since they would exist even in the absence of a TMI. The sets of route options and the RTCs associated for these trajectories, however, are not self-evident, and must be synthesized using some model of air carrier preferences.

To represent the TOSs, we have formulated a model to represent how these alternate route options might be expressed by the flight operators/airlines as shown in Figure 5.

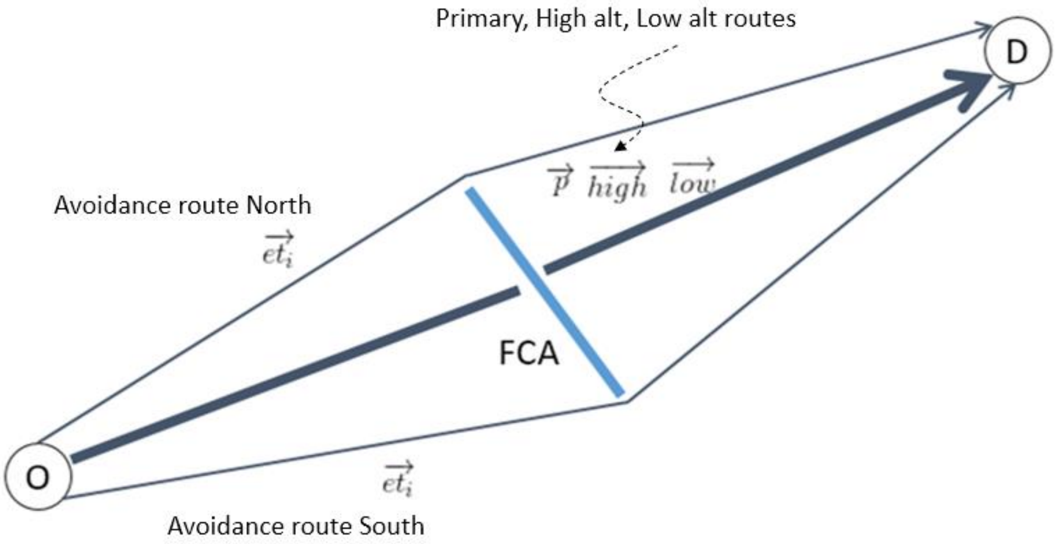


Figure 5: Representation of trajectory/route options in a TOS

The model proposes four trajectories:

- The primary trajectory ($\vec{p}$) is the filed flight plan trajectory of the flight that is filtered by the FCA.
- The avoidance trajectory ($\overrightarrow{et_\iota}$), is the trajectory that has the least relative trajectory cost (RTC), out of the possible trajectories that avoid the FCA by going around it through way points near the extreme ends of the FCA.
- The low Altitude trajectory ($\overrightarrow{low}$), avoids the FCA by going below the altitude limits of the FCA, but otherwise following the geometry of the primary trajectory.
- The high altitude trajectory ($\overrightarrow{h\iota gh}$), is similar to the low altitude trajectory, except that it avoids the FCA by going at a higher altitude than the altitude limits of the FCA.

3.1. Cost functions for calculating Relative Trajectory Cost (RTC):

Relative trajectory cost (RTC), a key part of the TOS that specifies the cost of this route relative to the planned/primary trajectory, is expressed in terms of ground delay equivalent (GDE) minutes. Flight operators assign RTCs to each trajectory option in a TOS. They are calculated using a cost function adopted by flight operators and are translated into equivalent ground delay. Each flight operator may use a different preferred cost function to calculate RTCs, and none would be required to reveal how they computed these internal costs. We propose two cost functions to calculate the RTC value. The RTC of a trajectory option is defined by equations (1) and (2), the units of which are (initial) Ground Delay Equivalent (GDE) minutes. The function f_1 below gives the cost of the primary trajectory, and f_2 gives the cost of the alternate trajectories.

Primary trajectory cost:

$$f_1(x_1) = x_1 + b(x_1 - g_0)^+ \tag{1}$$

Alternative trajectory cost:

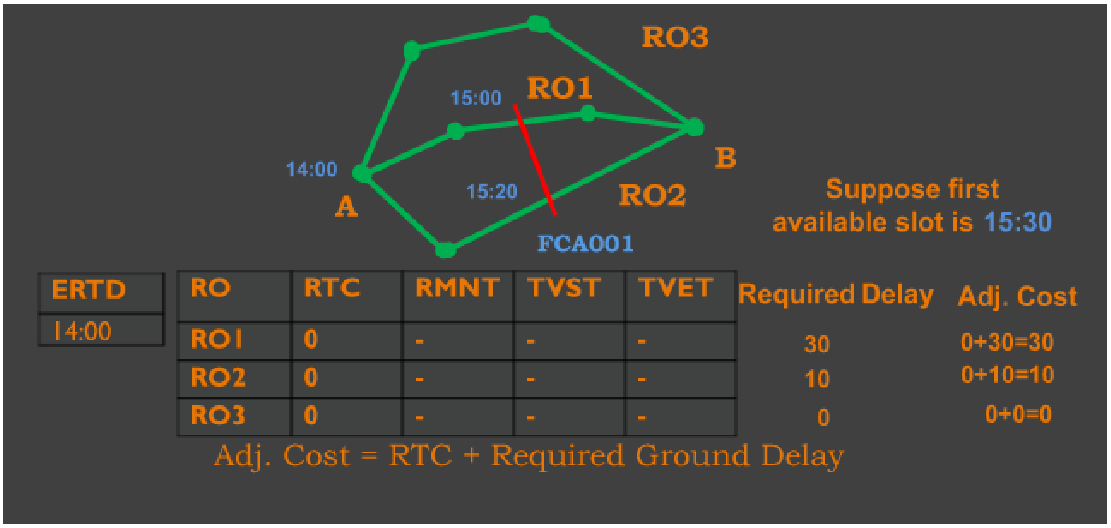
$$f_2(x_2,\ y_2,\ z_2,\ h_2) = y_2 + x_2 + ay_2 + b(x_2 + ay_2 - g_0)^+ + cz_2 + dh_2 \tag{2}$$

Where

- x_1 = ground delay minutes assigned on the preferred/filed trajectory
- x_2 = ground delay minutes assigned on the alternate trajectory
- y_2 = additional minutes incurred by the aircraft for flying the respective trajectory
- z_2 = time of flight on the low-altitude trajectory
- h_2 = time of flight on the high-altitude trajectory

- g_0 = delay threshold in GDE minutes, the time after which ground cost jumps significantly
- a, b, c, and d are cost parameters and have no units

The variables x_1, y_2, z_2 and h_2 are straightforward. From Chapter 2, we know that the CTOP allocation algorithm will calculate the adjusted cost for each route option in the TOS. The adjusted cost is the summation of the RTC and the required ground delay for the candidate trajectory; this required ground delay is x_2 (Figure 6). The motivation behind introducing g_0, the ground delay threshold, is that there will be some maximum amount of ground delay that the flight operators/airlines would be willing to accept for a flight, such that the ground delay assigned will not have an impact on the individual flight's schedule or its fleet schedule. This could be based on numerous factors like connecting flights, crew operations, gate assignment, etc. The cost/impact of ground delay might significantly increase once the assigned ground delay exceeds this value due to the characteristics of an individual flight; that additional cost per-GDE minute is given by b. The amount of increase in cost could vary a lot, depending on the flight and flight operator in question. The parameter a is the excess cost per minute of air delay versus ground delay. The parameter c converts the excess cost of a low-altitude flight minute into equivalent ground delay minutes. The parameter d converts the excess cost of a high-altitude flight minute into equivalent ground delay minutes, if any. The notation $(expression)^+$ returns $(expression)$ if $(expression)$ is greater than 0 and otherwise returns 0.



ERTD
14:00

RO	RTC	RMNT	TVST	TVET	Required Delay	Adj. Cost
RO1	0	-	-	-	30	0+30=30
RO2	0	-	-	-	10	0+10=10
RO3	0	-	-	-	0	0+0=0

Adj. Cost = RTC + Required Ground Delay

Figure 6: Calculation of adjusted cost for route options in a TOS (FAA, 2014)

For the purpose of simulation, certain assumptions have been made about the values of these parameter values and how could they be expressed. For example, one might expect the cost of delay to jump around 30 GDE minutes. Flights that experience delay less than 15 minutes are still considered to be on time, so perhaps a good threshold limit for flight operators would be twice this value, but it could be less or more depending on the flight operator. Thus, in a simulation we might make g_0 uniformly distributed between 20 and 40 GDE minutes. The marginal cost of delays above this threshold, b, could vary among the flight operators, and it could even vary among the flights of an individual flight operator. For simulation purposes, we have represented it using a uniform distribution between 2 and 10. Among the aviation field a is generally considered to be 2, as it is a common rule of thumb to consider one unit of air delay equivalent to two minute of ground delay (see for example Ball et al., 2003; Liu and Hansen, 2014; and Bertsimas and Patterson, 2000). For simulation purposes, to allow some variance, we model a as uniformly distributed between 1.8 and 2.2. Currently, c is modeled as a constant 0.1, although with more information one could also apply a probability distribution. It relates to excess fuel burn due to flying at low altitude as the higher air density at low altitudes decreases flight efficiency by increasing the skin-friction drag produced by the interaction of air molecules with the surface of the aircraft. The actual value would depend on a combination of various factors: the fuel market price, type of aircraft, payload, and the flying altitude. The intuition behind d is that for an aircraft to fly at high altitudes, although the flying is more efficient once the aircraft gets there, the aircraft must first climb to that altitude, which requires additional lift and increased speed. As a result, the aircraft engines rotate at high rpms during the climb, thus leading to a higher fuel flow into the engines. However, the low fuel burn when flying at high altitudes may remediate this, if this segment of the flight is long enough. Of course, this is the reason that aircraft fly at relatively high altitudes to begin with. It is also important to understand that different aircraft have different operating envelopes, leading to different restrictions on how high they can fly.

To calculate y_2, we need to find the additional flight time on an alternate trajectory in comparison to the primary/pre-filed trajectory. This is done by finding the difference in distance between the primary trajectory and alternate trajectories and dividing it by the average speed of the aircraft. To find the difference in distance we need to find the distances shown in Figure 8 (OP, PD, OE_1, OE_2, E_1D, E_2D). To compute the distance between two coordinates we use the Haversine formula (Equation 3 and Figure 7), which calculates the great-circle distance between two points – the shortest distance over the Earth’s surface, and Pythagoras’ formula.

$$haversine\left(\frac{d}{r}\right) = haversine(\phi_2 - \phi_1) + \cos(\phi_1)\cos(\phi_2)\, haversine(\lambda_2 - \lambda_1) \qquad (3)$$

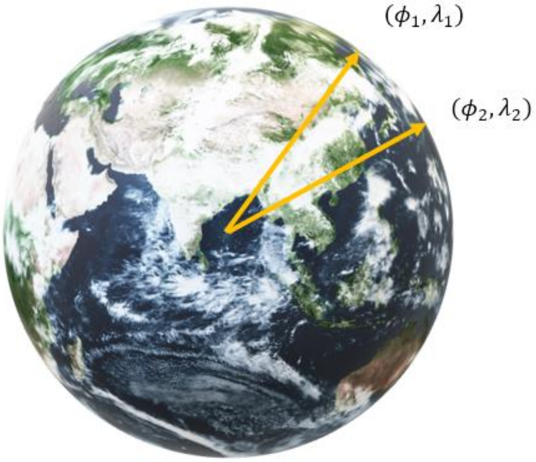


Figure 7: Haversine formula

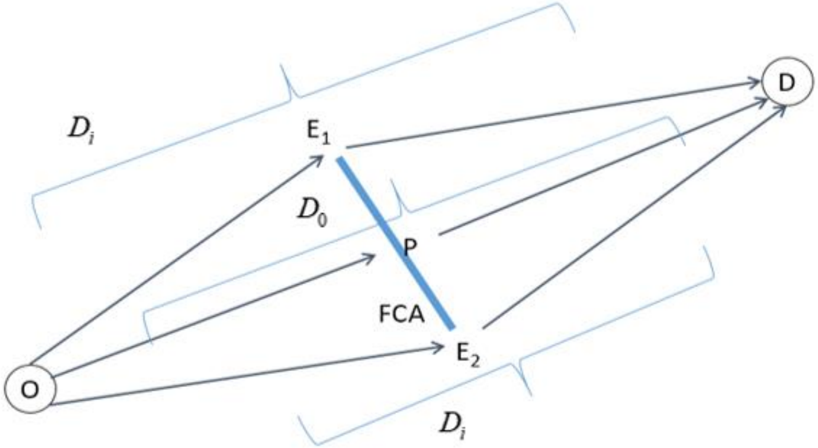


Figure 8: 2D representation of TOS

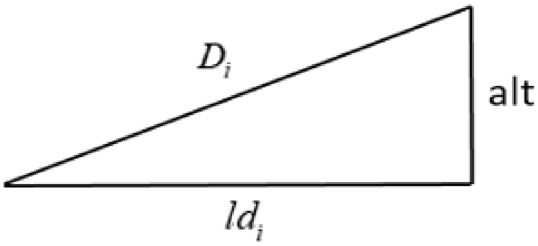


Figure 9: Calculating flight distance

The distance D_i for trajectory i (primary: 0, alternate: i) is the flight’s distance from its origin to its destination, *alt* is the altitude attribute of the flight at the FCA (the altitude at which a flight will pass through the FCA; this is assumed to be the flight's cruising altitude for simplicity), ld_i = haversine (coordinate_1, coordinate_2) in nautical miles.

$$ld_0 = \left|\overrightarrow{OP}\right| + \left|\overrightarrow{PD}\right| \tag{4}$$

$$ld_i = \overline{|OE_\iota|} + \left|\overrightarrow{E_\iota D}\right|, i = 1, 2$$

$$D_0 = \sqrt{alt^2 + ld_0^2} \tag{5}$$

$$D_i = \sqrt{alt^2 + ld_i^2}\,, i = 1, 2$$

$$y_2 \ = \ (D_i - D_0)/avg.\, aircraft\ speed\ in\ nautical\ miles\ per\ minute \tag{6}$$

3.1.1. *Calculating Relative Trajectory Cost for trajectories:*

The Relative Trajectory Cost (RTC) for each trajectory option in the TOS specifies the cost of the route relative to the planned/primary trajectory. To find the RTC, we set RTC to the minimum value of x_1 such that,

$$f_1() \ \geq \ f_2() \tag{7}$$

When we set $x_2 = 0$, the ground delay assigned to the candidate alternate trajectory is zero. The minimum value of x_1, is the value of x_1 such that the two functions are equal. Thus, the RTC will be the value of x_1 such that:

$$f_1(x_1) = f_2(0, y_2, z_2, h_2) \tag{8}$$

If we set $k = f_2(0, y_2, z_2, h_2)$, then we have

$$RTC = \begin{cases} k & if\ k <= g_0 \\ g_0 + \dfrac{k - g_0}{b+1} & if\ k > g_0 \end{cases} \tag{9}$$

Chapter 4: CTOP resource allocation policy

The present version of CTOP performs route and delay assignment using a Ration by Schedule (RBS) policy, which is based on the First Come First Served (FCFS) principle. In this thesis, we propose four alternate allocation approaches that could be used to perform route and slot assignment in a CTOP. The motivation behind these approaches was the room for improvement in the performance of the present allocation policy used in CTOP. We have used a simple stylized analytical model to show that there is room for improvement in the present form of CTOP. Resource allocation strategies in general are influenced by three factors: what resources are to be allocated, what allocation standards and principles are to be used, and which algorithm is to be adopted. In CTOP, the resources that the flights and the airlines/flight operators compete for are the FCA capacities (FAA, 2014). Slot-based allocation is the approach used in GDPs and AFPs by the FAA; CTOP is no different in that respect. The FAA uses a slot-based RBS allocation, based on the FCFS principle with respect to initial scheduled arrival times for CTOP. The flights affected by the CTOP are sorted by their earliest Estimated Time of Arrival at the FCA (ETA), creating the Initial Arrival Time (IAT) order. The FAA allocates the slots to flights and makes rerouting decisions based on the adjusted cost; the CTOP allocation algorithm will calculate the adjusted cost for each route option in the TOS. If the ground delay assigned on the primary trajectory exceeds the adjusted cost of a route option in the TOS, the flight is rerouted.

In slot-based allocation, each time interval at the FCA is subdivided into equal time slots, with each slot assigned to no more than one flight. The number of slots within the time interval and the slot duration depends on the FCA capacity, this is known as the rate of the FCA for a given time. It is usually expressed as the number of flights that can be processed at the FCA; e.g. 60 flights per hour indicates that no more than 60 flights can pass through the

FCA per hour during the respective time interval, so there are 60 available slots during an hour period and each slot is a minute long. To understand the need for better allocation algorithms than the present RBS policy, we shall investigate the delay savings from implementing a CTOP, and how a CTOP impacts delay cost and trajectory choice as a function of various CTOP parameters. We describe models for determining the delay savings by CTOP.

The RBS policy is the most widely accepted notion of fairness in ATM, and hence it serves as a key underlying principle in the allocation processes used in TMIs like GDPs and AFPs. It has also been shown that RBS is the optimal allocation for a single resource problem (Vossen and Ball, 2006). From this point onwards, we will be addressing the current RBS allocation process used in a CTOP as CTOP_RBS. The algorithm of CTOP_RBS is as follows:

1. Consider a slot (in chronological order)
2. Find the list of flights that can be assigned to that slot
3. Sort the flights by their arrival time at the FCA
4. Calculate the delay for the earliest flight that can be assigned to the slot
5. If the delay (GDE minutes) for the flight is less than or equal to the adjusted cost of the nominal trajectory in the TOS
    a. Assign the slot to the flight, and the flight takes the ground delay assigned, if any
6. If the delay (GDE minutes) is greater than the adjusted cost of the nominal trajectory
    a. Reroute the flight to one of the trajectories from the TOS.
        i. When rerouting flights, assign the trajectory that has the least adjusted cost (summation of RTC and required ground delay for the candidate trajectory) from the TOS. The choice of trajectory impacts the decision to reroute or not, as the RTC of the trajectory is the deciding factor

This process (steps 1 through 6) is repeated until all possible slots within the CTOP period have been allocated.

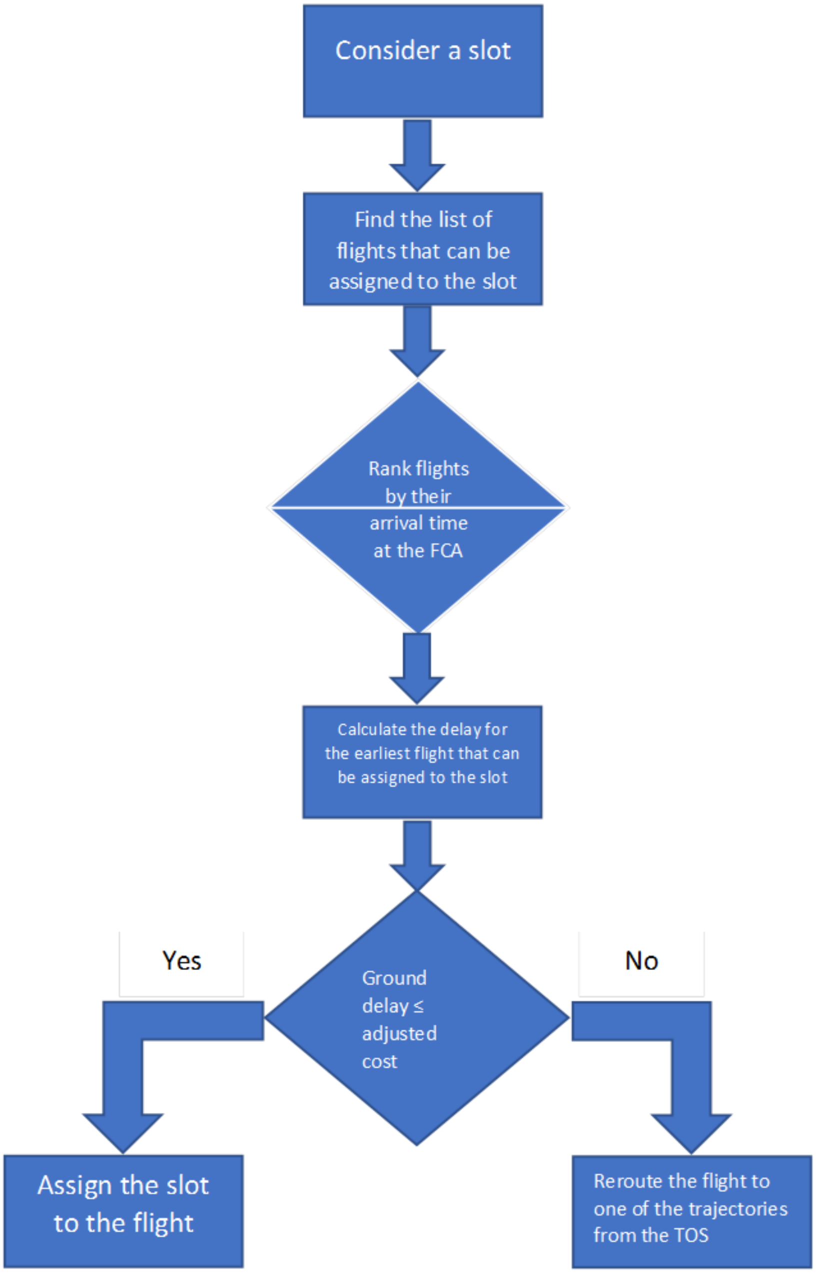


Figure 10: Flow chart of CTOP_RBS

We can apply a continuous approximation to study a CTOP under a single FCA. This will serve to illustrate some basic ideas and to give strategic insight for further analysis and CTOP planning. Assume that the capacity for the single FCA is given by R (flights per minute). For this exercise, also assume this is the rate at which flights are scheduled to approach the FCA. Let $NF(t)$ represent the cumulative number of flights that have passed the FCA boundary by time t. Also let $T(k)$ represent the time at which flight k reaches the FCA boundary. Then the following two equations hold:

$$NF(t) = Rt \tag{10}$$

$$T(k) = \frac{k}{R} \tag{11}$$

For example, with R = 0.5 flights per minute (30 flights per hour, 1 flight per 2 min, 30 equal slots of 2 min each): $NF(60) = 0.5 * 60 = 30$, 30 flights reach the FCA in the 1st hour and with R = 0.5 and k = 60; $T(60) = 60 / 0.5 = 120$ minutes, the time when the 60th flight reaches the FCA.

To investigate the delay savings by CTOP and the CTOP's impact on flight delays, we now consider that there is a reduction in FCA capacity, which leads to a reduction in the rate at which the FCA can process flights. As demand exceeds capacity, the FAA implements a TMI, which will lead to the initiation of a CTOP. We consider two cases to show the delay savings by CTOP. In the first scenario, a Ground Delay Program (GDP) is the TMI implemented by the FAA (assuming CTOP is not implemented). If we represent the capacity reduction by way of a rate reduction factor w, where $0 \leq w \leq 1$, then the new (reduced) rate will be wR. Let $D(k, w)$ represent the delay cost in Ground Delay Equivalent (GDE) minutes for the k^{th} flight under the reduced rate with factor w. If we change the $T(\cdot)$ function described above slightly to include w as a parameter, i.e., $T'(k, w)$ = the time the k^{th} flight reaches the FCA boundary under the reduced rate, then

$$T'(k, w) = k/(wR) \tag{12}$$

$$D(k, w) = T'(k, w) - T(k) = \left(\frac{k}{wR}\right) - \left(\frac{k}{R}\right) = \frac{k}{R}\left(\frac{1-w}{w}\right) \tag{13}$$

For example, with R = 0.5, w = 2/3 and we consider flight k = 40, then

$$D(k, w) = \frac{40}{0.5}\left(\frac{1-2/3}{2/3}\right) = 40 \text{ GDE minutes}$$

Assuming a continuous linear approximation, the total delay in units of flights-GDE minutes for k flights, denoted $TD(k, w)$, is the area under the graph in Figure 11.

$$TD(k, w) = \frac{1}{2}kD(k, w) = \frac{k^2}{2R}\left(\frac{1-w}{w}\right) \tag{14}$$

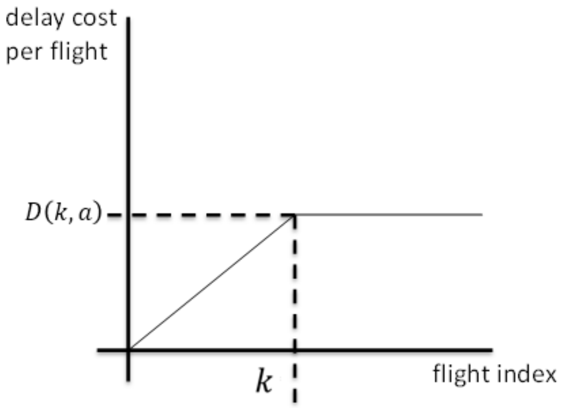


Figure 11: Delay cost per flight without CTOP vs flight index based on the Initial Arrival Time (IAT) order at the FCA

In the second scenario, instead of a GDP, the FAA implements a CTOP. Under CTOP, when a flight's delay is more than the adjusted cost of a trajectory from its TOS, the flight gets rerouted to the respective route option; adjusted cost is the summation of RTC and required ground delay for the candidate trajectory. It is important to note that in our analysis the required ground delay for the candidate trajectory is assumed to be zero, thus when a flight's delay gets large enough it will opt to one of the trajectories from its TOS completely based on its RTC.

For illustrative purposes, suppose that all flights have the same RTC, and that that value is p. Our goal is to show the delay savings by CTOP as well as to provide the basic ideas and strategic insight for further analysis and CTOP planning. If we let $D'(k, w, p)$ = the delay cost in Ground Delay Equivalent (GDE) minutes for the k^{th} flight under a CTOP with common RTC p, then

$$D'(k, w, p) = \min\left\{\frac{k}{R}\left(\frac{1-w}{w}\right),\ p\right\} \tag{15}$$

If we denote by k^* the flight index at which a flight first switches to it alternate route, and remember that such a switch necessarily occurs with ground delay equal to p, so that

$$\frac{k}{R}\left(\frac{1-w}{w}\right) = p \implies k^* = \frac{p\,R\,w}{1-w} \tag{16}$$

The total delay cost with CTOP can then be given (Figures 12 and 13) as:

$$TD'(k, w, p) = \begin{cases} TD(k, w),\ \ k \le k^* \\ TD(k^*, w) + p(k - k^*),\ \ k > k^* \end{cases} \tag{17}$$

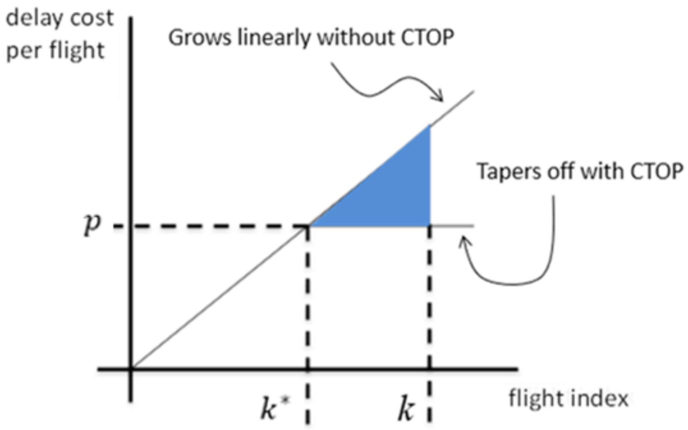


Figure 12: Plot of delay cost per flight with and without CTOP

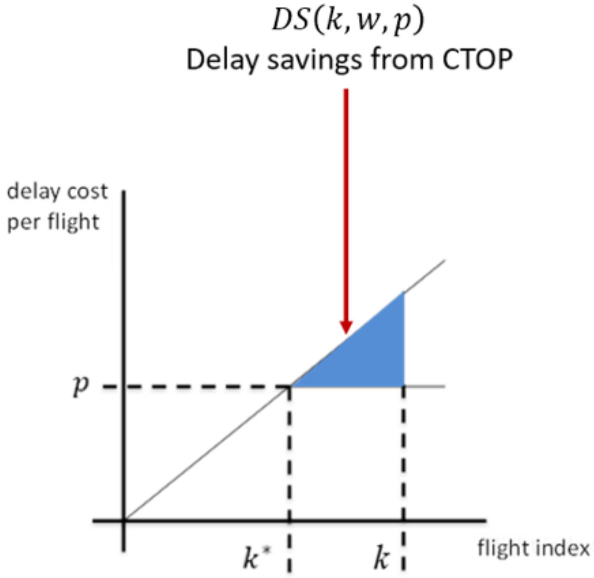


Figure 13: Delay savings by CTOP

The delay savings from CTOP can be computed as follows:

$$DS(k,w,p) = \begin{cases} 0, & k \leq k^* \\ TD(k-k^*,w), & k > k^* \end{cases} \tag{18}$$

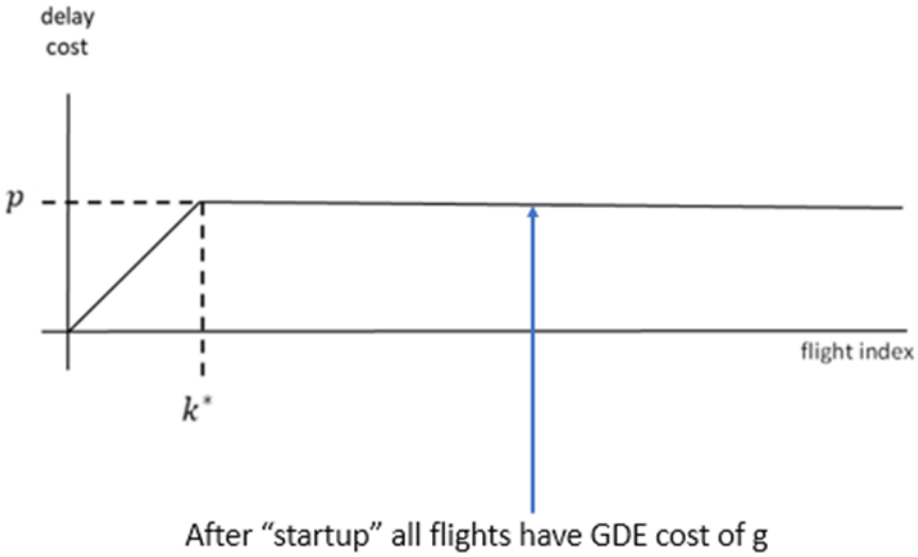


Figure 14: Delay cost per flight with CTOP vs flight index based on the Initial Arrival Time (IAT) order at the FCA

This analysis assumed a single FCA, a continuous buildup of flights, and an elevated level of certainty regarding delays/reduced capacity. We understand that in more dynamic/uncertain settings, things may be different. If there are multiple FCAs, things will become more complex. However, our goal was to show the delay savings by CTOP, provide basic ideas, and to give strategic insight to show the need for a better allocation policy. We will demonstrate that the proposed allocation mechanisms perform significantly better than CTOP_RBS by developing a more realistic test case in Chapter 7. From the analytical model we can see that incorporating rerouting as a control mechanism besides ground delay reduces total flight delays significantly, emphasizing the benefits of a CTOP program over the traditional TMIs like GDPs. It is also intuitively clear that it should not be necessary for all flights after the k^*threshold (Figure 14) to suffer a delay cost of p. This problem within the current allocation principle of CTOP (CTOP_RBS) brings up the space and need for a better allocation algorithm that minimizes the delay on flights arriving after the k^*threshold.

Chapter 5: Short queue allocation algorithm for CTOP

As discussed in Chapter 4, there is an improvement that can be made to the CTOP RBS, which brings up the need for a better alternative resource allocation method. This chapter describes the approaches developed and prerequisites for the same. We propose four approaches based on the principle that by building a queue of assignable flights at the slot and rerouting a percentage of flights so that the queue does not increase in size (maintaining the queue size at or below a fixed value), we can reduce the total delay and as a result increase the delay savings by CTOP. The approaches have a common parameter called Q_max, the maximum queue size. We will impose a (virtual) queue at the FCA, to ensure that it is saturated to the extent possible.

The four variations of short queue allocation algorithms are BPRA, RIBPRA, RIBPRA_E, and RIBPRA_RBS. Each is a form of priority resource allocation (PRA), and the details surrounding the naming of each are given in the sections below. The prerequisite for these algorithms is that in addition to the TOS submitted by flight operators for a flight they must specify a preference value for their flights. Flight operators (airline carriers) assign a preference value to each flight involved in CTOP, which is a way of indicating their own priority among their flights:

1. Preference value is an integer between 1 (lowest priority) and 5 (highest priority) (Vlachou and Lovell, 2013).
2. The average over all assigned preference values for a given carrier must be 3.

This provides flight operators the ability to express priorities over their flights. The current CTOP has the ability only for the flight operators to express their preferences for the alternate trajectories for a flight (by expressing RTC for the trajectories in a TOS), but does not allow them to distinguish the flights from each other in such a direct way. This will result in creating a platform for better knowledge sharing and thereby enabling the flight operators/airlines and the FAA to decide on which flights must be allocated a slot or given access to constrained air space (FCA) and flights to be rerouted. The secondary motivation for introducing a preference value that indicates a priority order of flights is that flight operators do not have a say in which flights get allocated a slot at the FCA and which flights get rerouted within the current framework of CTOP. In Chapter 6, we explain how the flight operators/airlines can assign the preference values to their flights.

To increase the delay savings by a CTOP and decrease the total delay, it is imperative to choose judiciously which flights are going to be allocated slots at the FCA and which are going to be rerouted. The rerouting control mechanism present in the current form of CTOP is very vulnerable. Flight operators could easily game the system by filing artificial RTC values for the route options in the TOS for a flight. It can be shown that RTC plays a key role in the decision of whether or not to reroute a flight. Under CTOP, when a flight's delay gets large enough, it will opt to one of the alternate trajectories. If the RTC is set to an exceptionally large value, the flight in question will fly its primary (filed) trajectory. Under the CDM environment it would not be hard for flight operators to figure out the flights competing for the same slot and try to game the system. This would not only impact the total delay assigned to its competitor's flights, but would also degrade the system efficiency. If all the flight operators employ this strategy of filing artificial RTC values for their flight's rerouting options, this would produce the same effect as if a traditional Ground Delay Program had been applied as the TMI, instead of the more contemporary CTOP.

Airlines are aware of CTOP's benefits and its vulnerabilities, which leads to their concerns about the amount of information that might be required to share while participating in CTOP (Vlachou and Lovell, 2013). To encourage the airlines/flight operators to submit this information about the relative priority of their flights and ensure the system is less prone to gaming, we impose the constraint that the average over the preference values for a given airline must be 3. This is to prevent the airlines from simply assigning all their flights a preference value of 5.

It is important to note that with the resource allocation process under the CDM paradigm using RBS (Figure 15), the RBS process is followed by a cancellations and substitution process, where airlines may cancel flights and modify slot-to-flights assignments for its own flights (intra-airline exchange) by exchanging the slots within its flights. Finally, "compression" is carried out by the FAA, which maximizes slot utilization by performing an inter-airline slot exchange to ensure that no slot goes unused. After the round of cancellations and substitution, the utilization of slots can usually be improved. The reason for this that *an airline's flight cancellations and delays may create "holes" (slots without a flight) in the current schedule* (Ball et al., 2007). For a detailed explanation of the cancellation, substitution, and compression processes, and how these "holes" might occur, the reader is referred to Ball et al., 2007. One of the reasons to have the airlines express their priority of flights involved in our proposed approach is to try to subsume the cancellation, substitution, and compression steps within our allocation algorithm. To be clear, however, the algorithm does not cancel any flights – this is a decision that is ultimately made only by the carrier. The goal is to allow carriers' most valued flights to receive the most favorable treatment, within that carrier's fair allotment of resources, to mitigate what would have been the need for most cancellations under earlier generations of TMIs. Of course, some cancellations are still likely to occur.

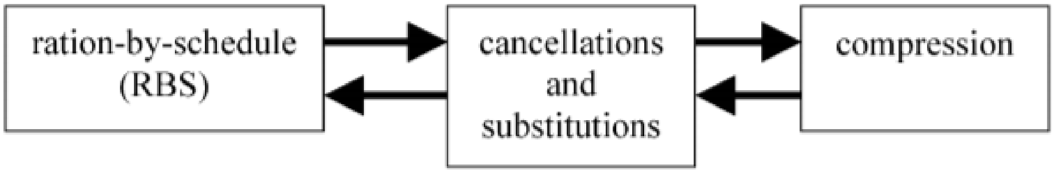


Figure 15: CDM resource allocation process (Ball et al., 2007)

5.1. <u>Balanced Priority Resource Allocation (BPRA)</u> (Ball, 2018):

The first allocation method presented here is the Balanced Priority Resource Allocation (BPRA) algorithm. The BPRA algorithm allocates slots to flights based on the order that is derived from the IAT of flights at the FCA, in the same way as the RBS policy, which is based on the FCFS principle. The difference between BPRA and CTOP_RBS is how the rerouting decision is made and which flight is rerouted. In BPRA, the rerouting decision is based on the parameter Q_max, the maximum queue size, unlike in CTOP_RBS, where the decision to reroute is not made until the delay experienced by a flight exceeds the adjusted cost of the nominal trajectory. Once the size of the queue of assignable flights at the slot exceeds Q_max by one, the flight with the lowest preference value is rerouted and removed from the queue. As a part of this allocation, we introduce a metric that will be dynamically computed for each airline based on the number of flights rerouted and the flights processed; see equation (19). This is to ensure that an airline that has more flights arriving late into the queue does not get penalized, and attempts to address any equity concerns. The number of flights processed is the summation of the number of flights that have been assigned a slot at the FCA and the number of rerouted flights for each airline. We make the following assumption: the prerequisite for the algorithm is that in addition to the TOS submitted by flight operators for a flight they must specify the preferences for their flights as described above and adhere to the rules developed in assigning these preference values.

Reroute rate ($\boldsymbol{R-rate}$):

$$R-rate = \frac{Number\ of\ flights\ rerouted}{Number\ of\ flights\ processed} \tag{19}$$

The algorithm of the allocation is as follows (Figure 16):

1. Consider a slot (in chronological order)
2. Find the list of flights that can be assigned to the slot
3. Sort the flights by their arrival time at the FCA
4. If the queue size is greater than or equal to $Q\_max + 1$
    a. Consider only flights within $Q\_max\ + 1$ from the formed queue
    b. Reroute and remove the flight with the lowest preference value from the queue
        i. In the case of a tie, choose the airline with the lowest $R - rate$ value
        ii. When rerouting flights, assign the trajectory that has the least adjusted cost (summation of RTC and required ground delay for the candidate trajectory) from the TOS. The choice of trajectory does not factor into the decision of whether or not to reroute, since it is based on the preference value.
    c. Repeat step 4 until the queue length is equal to Q_max
5. If the queue size is less than or equal to Q_max
    a. Assign the slot to the first flight in the queue

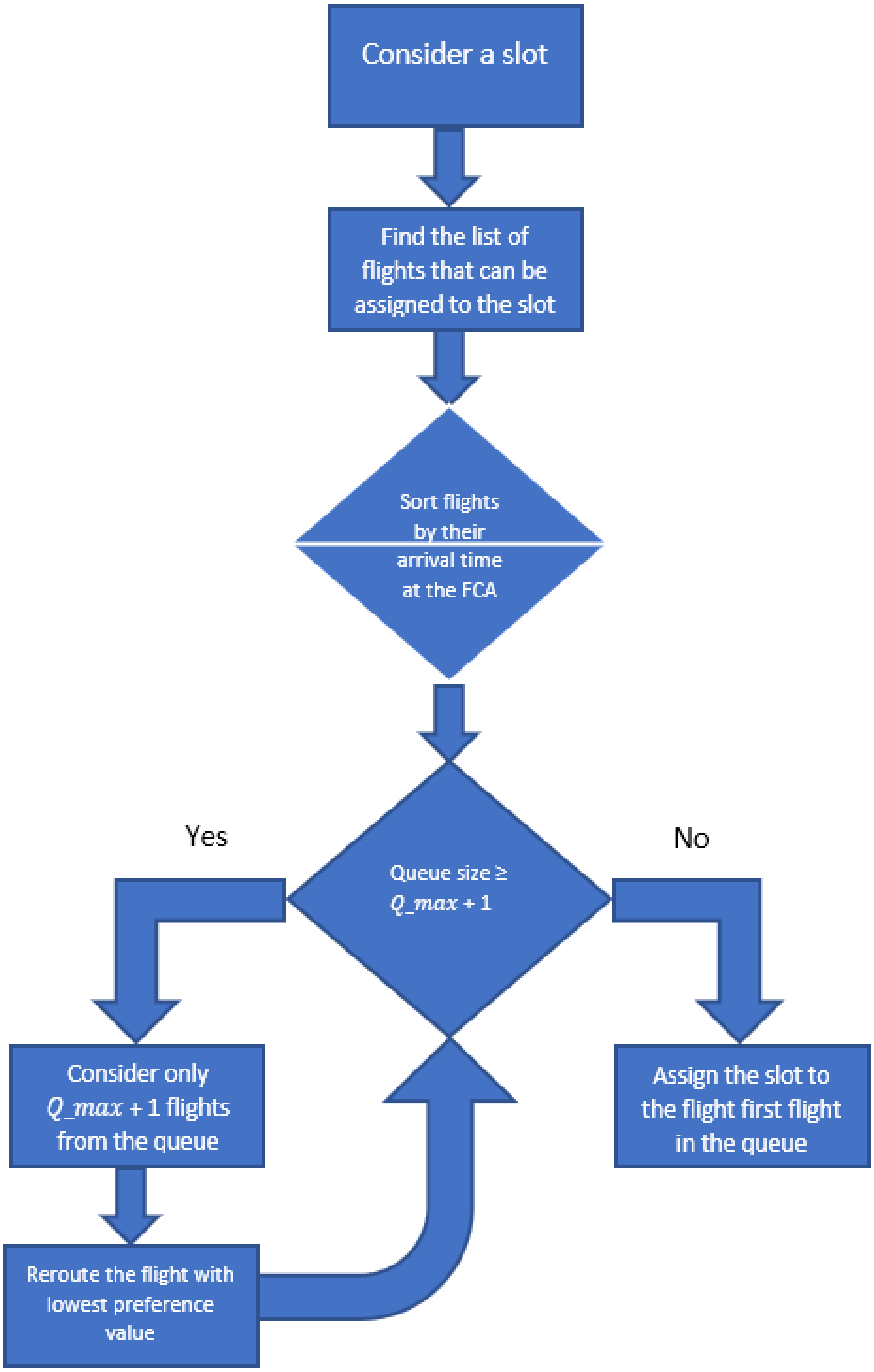


Figure 16: BPRA Algorithm

5.2. *Reroute Incentive Balanced Priority Resource Allocation (RIBPRA):*

We understand that it is imperative to identify the flights that need to be rerouted and the flights that must be allocated slots. This could be done only if the preference values presented are truthful. To further encourage the flight operators to provide the preference value for their lights, we introduce a dynamically maintained incentive metric called $Ri - factor$ (Equation 20).

$$Ri - factor = \boldsymbol{\Sigma}\, priority\ of\ rerouted\ flights \tag{20}$$

We make changes to the decision principles that dictate the allocation of slots and reroutes. It can also be seen that we have shifted from a slot-to-flight allocation to a pseudo flight-to-slot allocation scheme. The RIBPRA algorithm is as follows (Figure 17):

1. Consider a slot
2. Find the list of flights that can be assigned to the slot
3. Sort the flights by their arrival time at the FCA
4. If the queue size is greater than or equal to $Q\_max\ + 1$
    a. Consider only flights within $Q\_max\ + 1$ from the formed queue
    b. Reroute and remove the flight with lowest sum of preference value and $Ri - factor$ from the queue
        i. In the case of a tie, choose the flight from the airline with the lowest $R - rate$ value
        ii. When rerouting flights, assign the trajectory that has the least adjusted cost (summation of RTC and required ground delay for the candidate trajectory) from the TOS. The choice of trajectory does not factor into

        the decision of whether to reroute the flight or not, as it is based on the priority rather than the adjusted cost of a trajectory.

    c. Repeat step 4 until the queue length is equal to Q_max

5. If the queue size is less than or equal to Q_max
    a. Assign the slot to the flight that has the largest sum of preference value and $Ri - factor$ in the queue
        i. In the case of a tie, choose the flight with the higher preference value

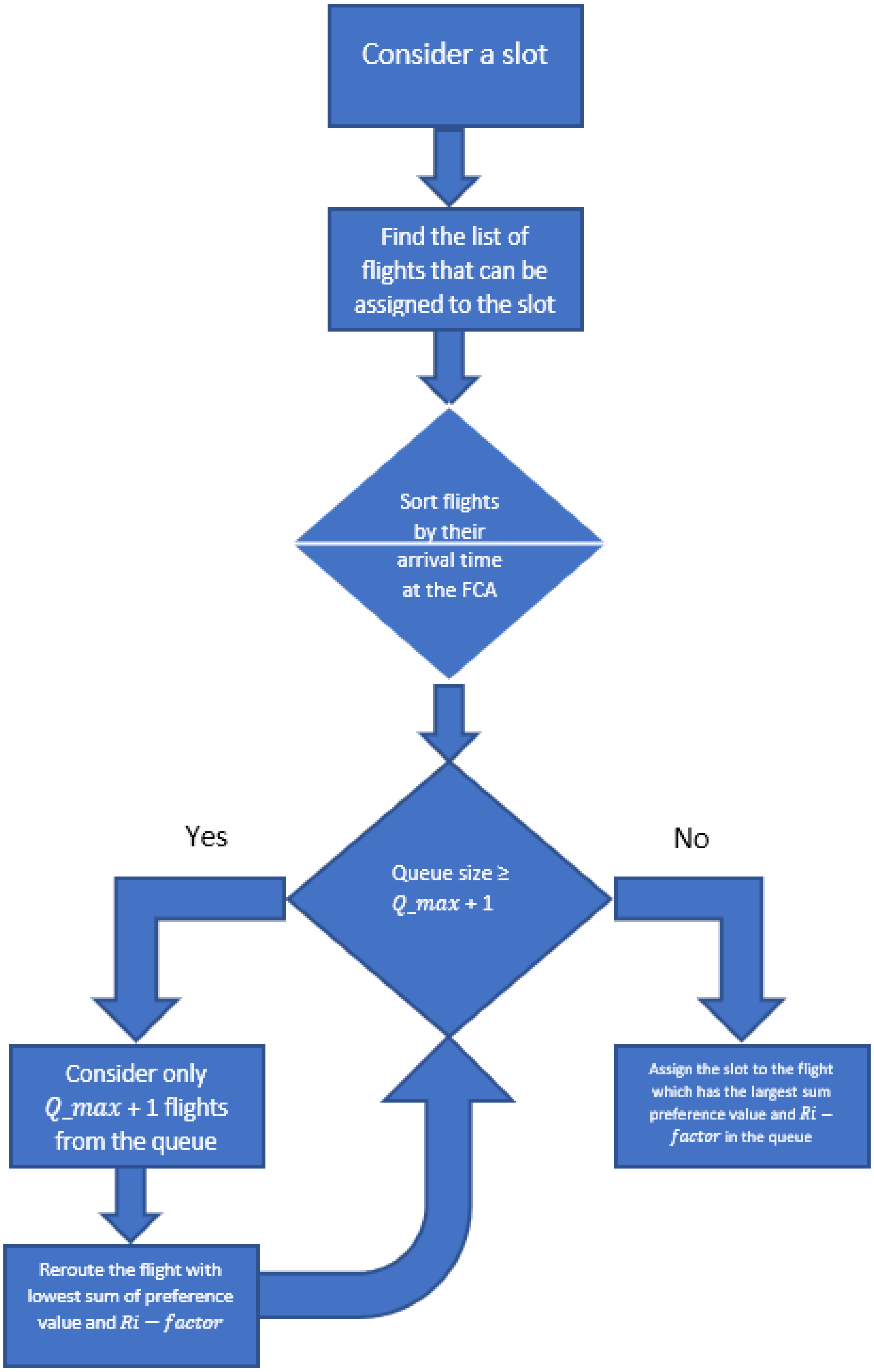


Figure 17: RIBPRA Algorithm

5.3. *Modified Reroute Incentive Balanced Priority Resource Allocation (RIBPRA_E):*

Equity concern is of prime importance when choosing an algorithm. One of the ways to ensure equity in an algorithm is by making sure that the algorithm avoids disparity and efficiency is transferred across the participants. In the analysis that will be shown later, Figures 33, 41 and 43 demonstrate that the RIBPRA allocation algorithm provides an advantage to big carriers or flight operators who have a high percentage of flights under a CTOP. To get rid of this undesired property in RIBPRA, we change the incentive metric to represent the average value of $Ri - factor$. The new incentive metric is called $ARi - factor$ (Equation 21).

Average reroute metric ($ARi - factor$):

$$ARi - factor = \frac{\boldsymbol{\Sigma} preference\ value\ of\ rerouted\ flights}{Number\ of\ flights\ rerouted} \tag{21}$$

The RIBPRA algorithm is as follows (Figure 18):

1. Consider a slot
2. Find the list of flights that can be assigned to the slot
3. Sort the flights by their arrival time at the FCA
4. If the queue size is greater than or equal to $Q\_max\ + 1$
    a. Consider only flights within $Q\_max\ + 1$ from the formed queue
    b. Reroute and remove the flight with the lowest sum of preference value and $ARi - factor$ from the queue
        i. In the case of a tie, choose the flight from the airline with the lowest $R - rate$ value

        ii. When rerouting flights, assign the trajectory that has the least adjusted cost (summation of RTC and required ground delay for the candidate trajectory) from the TOS. The choice of trajectory does not factor into the decision of whether to reroute the flight or not, as it is based on the priority rather than the adjusted cost of a trajectory.

    c. Repeat step 4 until the queue length is equal to Q_max.

5. If the queue size is less than or equal to Q_max

    a. Assign the slot to the flight that has the largest sum of preference value and $ARi - factor$ in the queue.

        i. In the case of a tie, choose the flight with the higher preference value

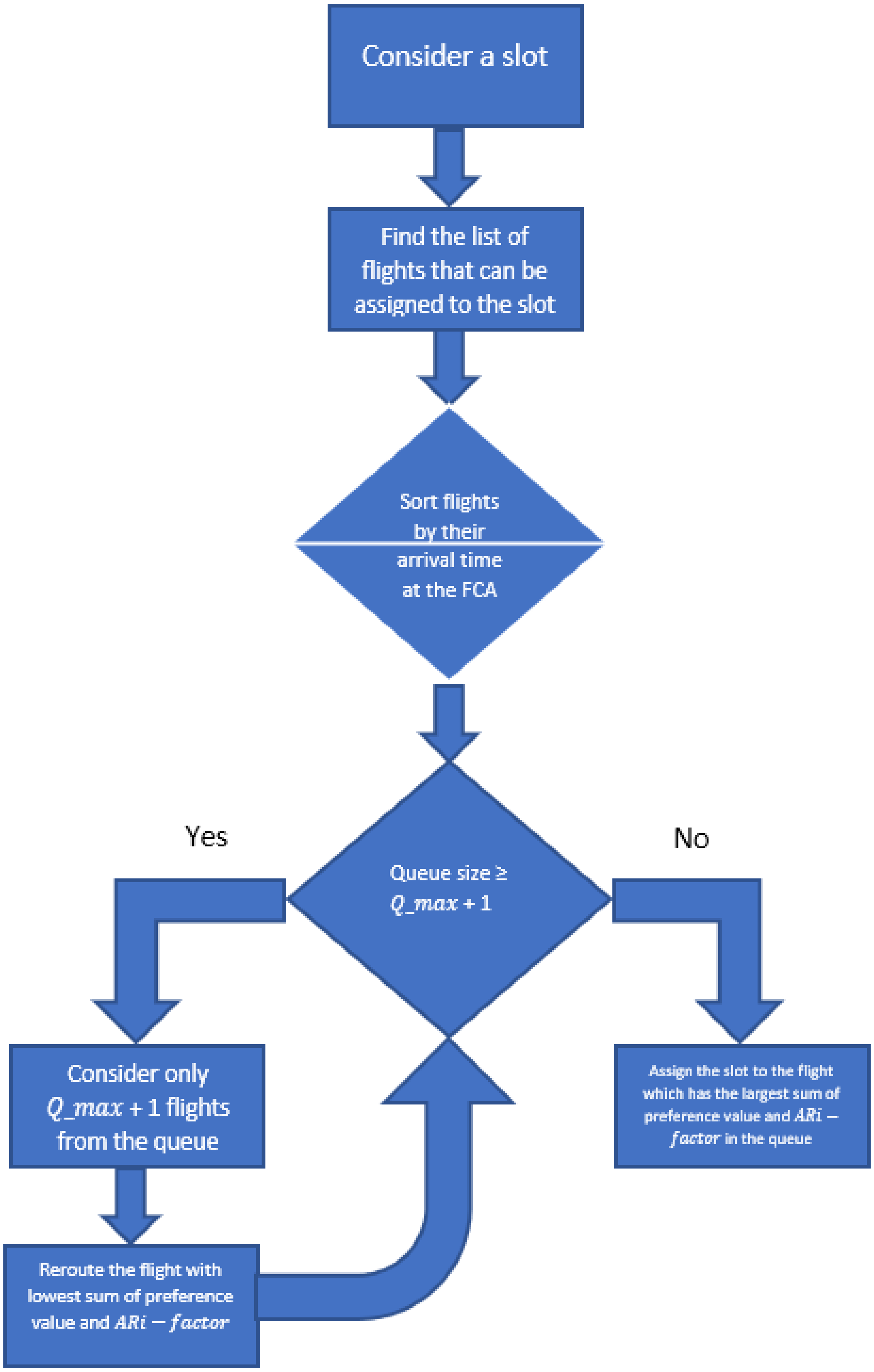


Figure 18: RIBPRA_E Algorithm

5.4. Reroute Incentive Balanced Priority Resource Allocation based on RBS (RIBPRA_RBS):

The final allocation method is a variation of the RIBPRA_E algorithm, which is also modified to reflect the importance of equity in the allocation process. It is like the BPRA algorithm in how it allocates slots to flights. It must be noted that both of these algorithms, BPRA and RIBPRA_RBS, also address the equity issue by adopting a First Come (scheduled) First Served (FCFS) principle (RBS policy) to allocate slots to flights. There are several equity criteria (Wanke et al., 2006) that can be considered, but no one of them is universally accepted. On the other hand, there have been several studies that address equity by defining the flight priority order and scheduling flights in the order using FCFS, which is considered to be equitable by the FAA and flight operators (Ball et al., 2005; Hoffman et al., 2005; Ball et al., 2010; Jakobovits et al., 2005; and Burke, 2002). The reasoning behind this is the fact that the flights are scheduled by the respective carriers/flight operators; the carriers would have made changes to this order if they would have wanted to implement a change.

The RIBPRA_RBS algorithm is as follows (Figure 19),

1. Consider a slot
2. Find the list of flights that can be assigned to the slot
3. Sort the flights by their arrival time at the FCA
4. If the queue size is more than or equal to $Q\_max + 1$
    a. Consider only $Q\_max + 1$ flights from the formed queue
    b. Reroute and remove the flight with the lowest sum of preference value and $ARi - factor$ from the queue
        i. In the case of a tie, choose the flight from the airline with the lowest $R - rate$ value

        ii. When rerouting flights, assign the trajectory that has the least adjusted cost (summation of RTC and required ground delay for the candidate trajectory) from the TOS. The choice of trajectory does not factor into the decision of whether to reroute the flight or not, as it is based on the priority rather than the adjusted cost of a trajectory.

    c. Repeat step 4 until the queue length is equal to Q_max

5. If the queue size is less than or equal to Q_max

    a. Assign the slot to the first flight in the queue

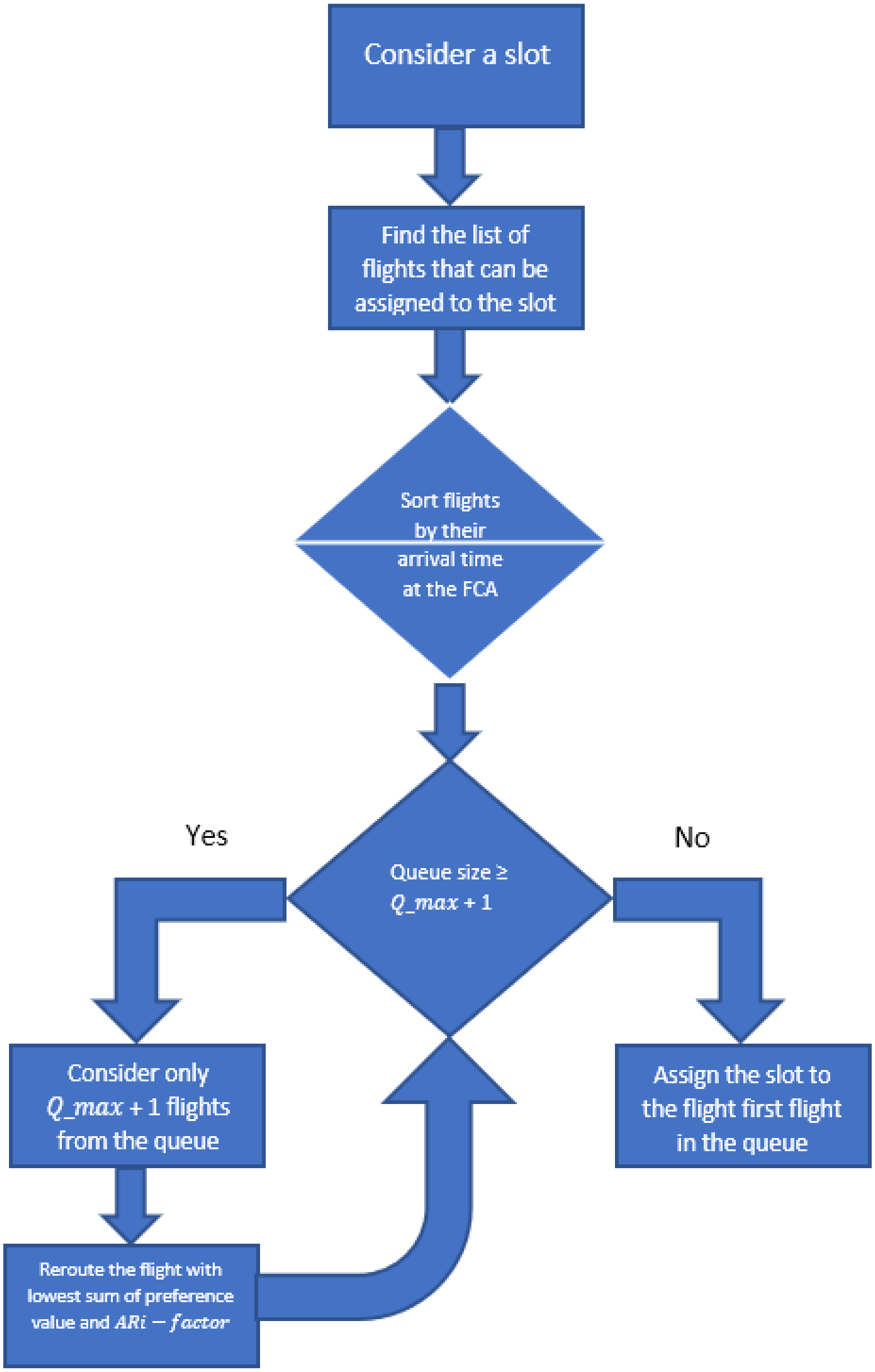


Figure 19: RIBPRA_RBS Algorithm

Chapter 6: Model for assigning preference values for flights

The proposed allocation approaches require that each airline assign a preference value ranging from 1 to 5 to each of their flights in a CTOP. The preference value reflects the relative priority of flights under the respective airline, from flights that the airline would not mind if they get rerouted (preference value 1), to flights that they do not want to get rerouted and suffer huge delays (preference value 5), and other dispositions in between. We describe four different strategies that could be employed by the airlines to assign preference values based on a simple linear weighted score function. Let F_a be the set of flights in a CTOP that belongs to airline a from the set of airlines A. For every flight f from F_a, V_f (Equation 22) is the measure of relative flight value, where u_i is assigned a value based on the aircraft size, duration of flight, number of passengers and number of passengers with connecting flights, etc. P_f, the preference value, is based on the weighted score TS_f for each flight f. $SRTC_f$ is the measure of relative flight value based on the RTC, where RTC_i is the nominal RTC value for flight i from its respective TOS. The weight factor t is specific to each airline but for the purpose of simulation, these are equally weighed. i.e. $t = 0.5$

$$V_f = u_f / \sum_{i \in F_a} u_i, \text{ where } u_i \in (0,\ 1) \tag{22}$$

$$SRTC_f = \frac{RTC_f}{\sum_{i \in F_a} RTC_i} \tag{23}$$

$$TS_f = tV_f + (1 - t)SRTC_f, for\ \forall\ f \in F_a\ \&\ a \in A \tag{24}$$

$$P_f = Q(TS_f) \tag{25}$$

We have identified three strategies that an airline could use to assign the preference value based on the weighted score TS_f for each flight f.

6.1. *Strategy I:*

Strategy I could be the strategy of no participation; i.e., the strategy could be employed to assign preference values for an airline that has decided not to participate in a CTOP or flight operators who have only one flight in a CTOP. It is as follows,

- Assign all flights Preference value 3
- $\mathrm{P_f} = Q(TS_f) = 3 \; \forall f \in F_a$

6.2. *Strategy II:*

Strategy II is the method we anticipate that a large section of the flight operators/airlines would be likely to employ. It is as follows,

- Equally assign Preference value 1-5,
    - 20% Preference value 1
    - 20% Preference value 2
    - ...
    - 20% Preference value 5

This could be achieved by the airlines by sorting their flights in a CTOP based on the weighted score TS_f, and then assigning preference value 1 to the first 20% of the flights in the order, preference value 2 to the next 20%, and so on. This could be employed by an airline only when the number of flights in a CTOP is divisible by 5. If the total number of flights is not divisible by 5, then let n be the remainder when the number of flights is divided by 5. For the final set of flights, assign priorities as follows:

- If $n = 1$, assign {3}
- If $n = 2$, assign {2, 4} or {1, 5}
- If $n = 3$, assign {2, 3, 4} or {1, 3, 5}

- If $n = 4$, assign $\{1, 2, 4, 5\}$

6.3. Strategy III:

Strategy III is very straightforward and simple: assign the preference value 2 or 1 to half of the flights in the CTOP, namely the flights with lower TS_f scores; assign the other half the preference value 4 or 5, respectively. For instances with an odd number of flights, assign the preference value 3 to the remainder.

6.4. Strategy IV:

Strategy IV is the only asymmetric strategy; meaning that it does not aim to assign equal numbers of 2's and 4's, or equal numbers of 1's and 5's, but nevertheless strives for the average priority across all flights to be 3. This strategy could be employed by an airline when it has, for example, more low priority flights and very few high priority flights. The assignment of preference value is solely based on an individual airline's operational requirement and flight priority. Figure 20 illustrates the possible number of combinations that can be achieved for the corresponding number of flights. The number of possible combinations for 10 flights is 34 and 28594 for 100 flights.

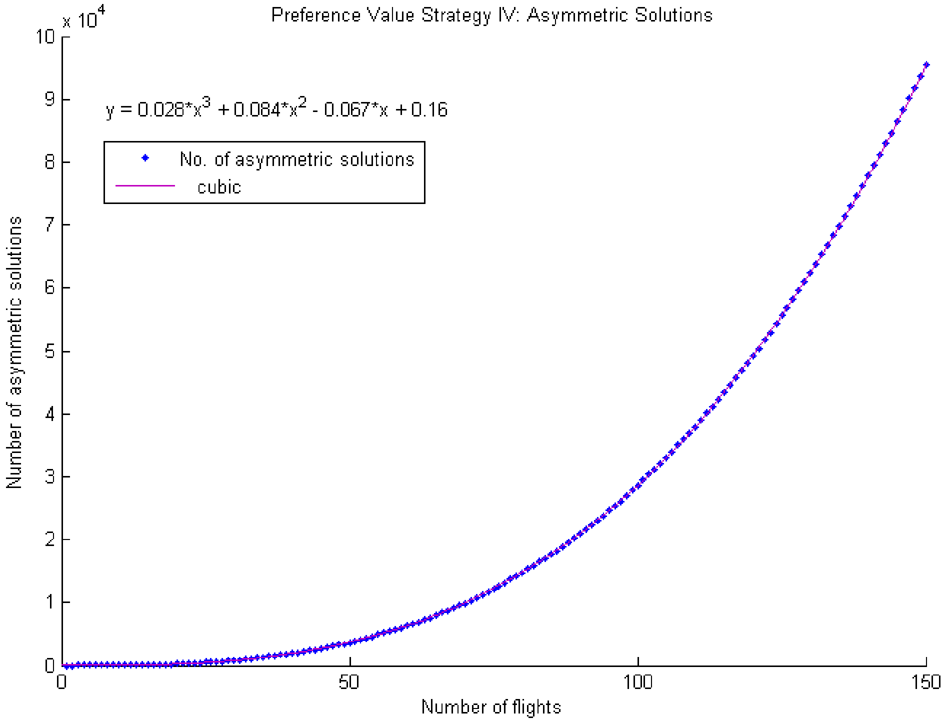


Figure 20: Possible asymmetric combinations for n flights

It might appear that such a preference value list is long and would be cumbersome for airlines/flight operators to produce. However, the airlines/flight operators would have all the information needed to produce the priority list, and this preference value is used only to represent the relative value of flights operated by the respective airlines/flight operator. Nevertheless, in the past when TMIs like GDPs and AFPs have been deployed, and cancellations and substitutions have been generated by carriers, there must have been some reasoning, coupled with numerical data, to support these choices. It is reasonable to assume that the generation of a list of preferences is no more onerous than what would have gone into this process. Furthermore, if a carrier does not want to bother, then a default assignment of priority 3 for all the flights could always be built into the system.

Chapter 7: Experimental Results and Discussions

To demonstrate the performance of our proposed allocation models, we describe a test case scenario where a CTOP is implemented by the FAA. The data used for the test case are the traffic demand data for the date 6 September 2016. These data contain the following fields: flight reference number, scheduled (planned) departure time, scheduled (planned) arrival time, planned cruise altitude level, aircraft type, waypoints of the planned route in LAT/LON LAT/LON format, aircraft tail number, origin airport, and destination airport. The data for our experiment were provided by Tim Myers and Dr. Robert Hoffman from Metron Aviation.

7.1. Boundaries of the experiment:

For our experiment, the test case scenario is based on a single FCA CTOP program. The FCA used is one from the list of canned FCAs (FCAA05) by the FAA. The FCA is used by the FAA to capture flights through Indianapolis Center (ZID) and Cleveland Center (ZOB) from the west, destined to airports in Northern Washington Center (ZDC), New York Center (ZNY) and Boston Center (ZBW). The FCA is located over the western boundary of ZOB and eastern boundary of ZID. See Figure 21 for an illustration of the FCA and the surrounding geography.

Figure 21: FCA, Geographical representation of the constrained airspace FCAA05

We developed a computer program using JAVA to obtain the list of flights captured by the FCA. The inputs are simply the flight traffic demand data for the specific date and the end coordinates of the FCA expressed in LAT/LON format. Only flights that had destination airports in the regions ZNY, ZBW and ZDC, and that had cruising altitude between 12000 ft. to 45000 ft. were considered. These filtering parameters are part of the dynamic nature of a regular FCA in a CTOP (Gaertner et al., 2007). The FCA was assumed to be active for a 4-hour period, starting at 1600 Zulu and ending at 2000 Zulu. A total of 313 flights were captured by the proposed CTOP test case scenario. The nominal capacity of the FCA was assumed to be 120 flights per hour, and the reduced capacity 60 flights per hr. The demand at the FCA on 9th September 2016 is illustrated in Figure 22.

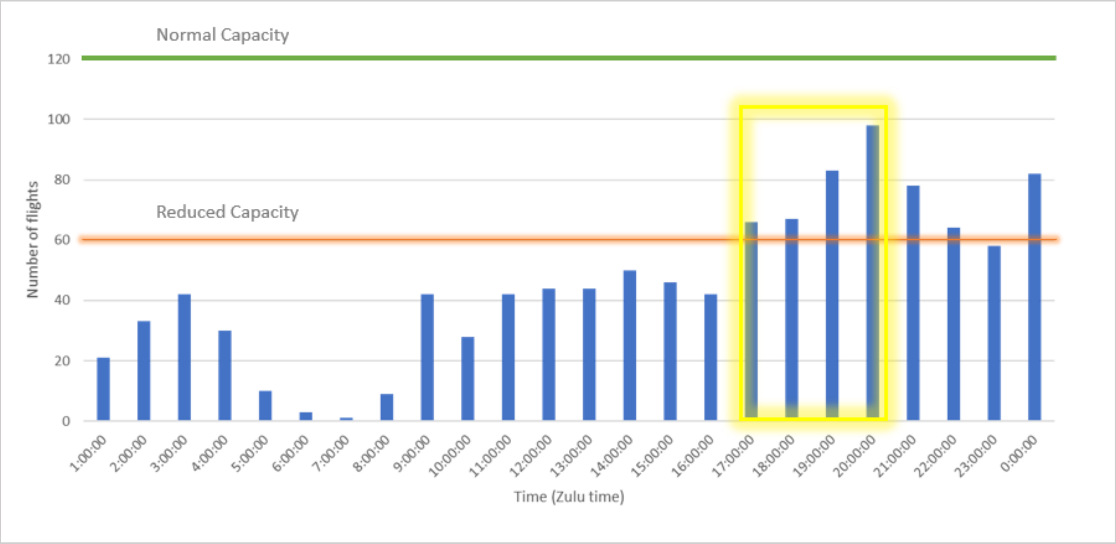


Figure 22: Demand at the FCAA05 on 9/6/2016

The initial arrival times of flights at the FCA were calculated based on their primary (filed) trajectories. For each flight, a TOS was modeled based on the model proposed under Chapter 3, and RTCs were calculated for the respective route options using the model proposed in Section 3.1. Flights were always rerouted to the trajectory with the least RTC, as it was assumed that the required ground delay for the trajectories in the TOS is zero. For the purpose of analysis the airlines/flight operators were assumed to employ Strategy II (Chapter 6.2) to assign preference values to their flights. The Required Minimum Notification Time (RMNT) for all flights in the test case CTOP was assumed to be 45 min, and the CTOP advisory notice was sent out at least 45 min earlier than the first scheduled flight captured by CTOP. The file time of a CTOP is important, as airborne flights cause huge delays to the system and they also lose the rerouting option if a CTOP was filed too late. The analysis of file time of a CTOP has its own research domain and will be not be considered here. Thus, it is assumed that the CTOP advisory notice is issued well in advance by the FAA to the airlines/flight operators and there is no risk of airborne flights.

7.2. *Comparison of the allocation schemes:*

We compare the results of the four proposed allocation methods against one another and with the existing CTOP allocation policy (CTOP_RBS). For the following set of results, we restrict the max queue in the BPRA, RIBPRA, RIBPRA_E, and RIBPRA_RBS algorithms to 6.

The key metric that exhibits the system efficiency performance measure of an allocation scheme is the total delay of the participating flights. From Figure 23, it is can be clearly seen that the proposed allocation methods' performance is significantly better than the existing allocation policy of CTOP (CTOP_RBS). RIBPRA and RIBPRA_E achieved a reduction of more than 50% in total delays when compared to CTOP_RBS while BPRA and RIBPRA_RBS achieved a reduction of slightly less than 50% in total delays. The performance superiority of the proposed algorithms over CTOP_RBS is clear.

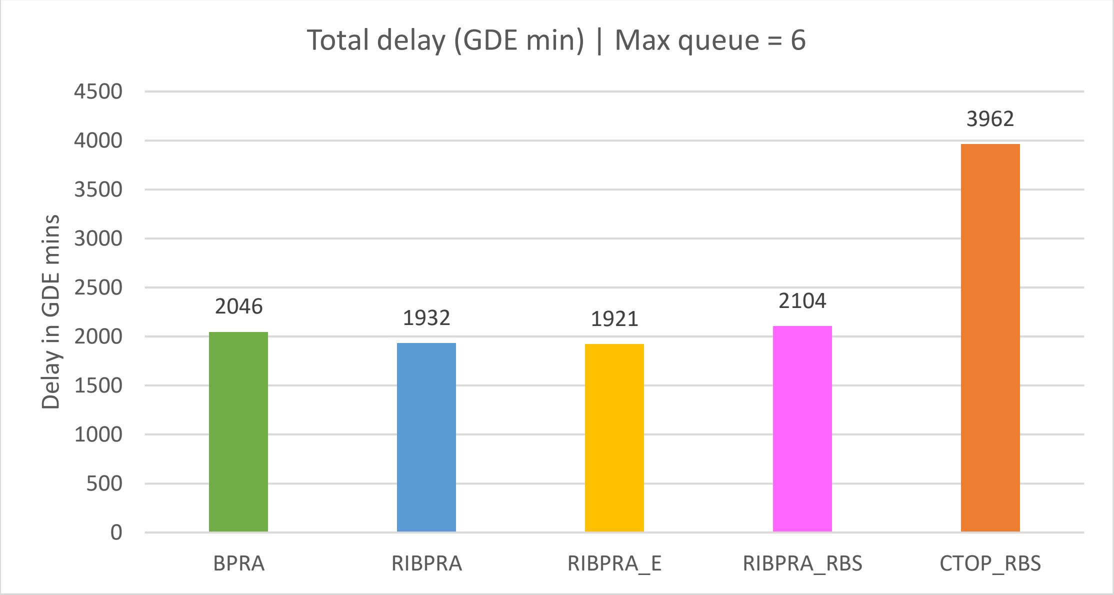


Figure 23: Total delay (GDE min) by allocation approaches

The total delay of flights has two hidden metrics within, the cumulative delay of flights that were assigned a slot and the cumulative delay of flights that were rerouted. Figure 25 shows how these metrics vary for the different allocation policies. As we predicted in Chapter 5 based on the analytical model, by rerouting a percentage of flights and thereby maintaining a small queue size, the delay savings from CTOP can be maximized; this is displayed in Figures 23 and 25. The delay accumulated on the flights assigned a slot is reduced considerably and because of rerouting a higher percentage of flights (Figure 24 and 25) there is an increase in the cumulative delay of rerouted flights. However, we can see that there is not a prominent difference in the average delay of rerouted flights from Figure 26.

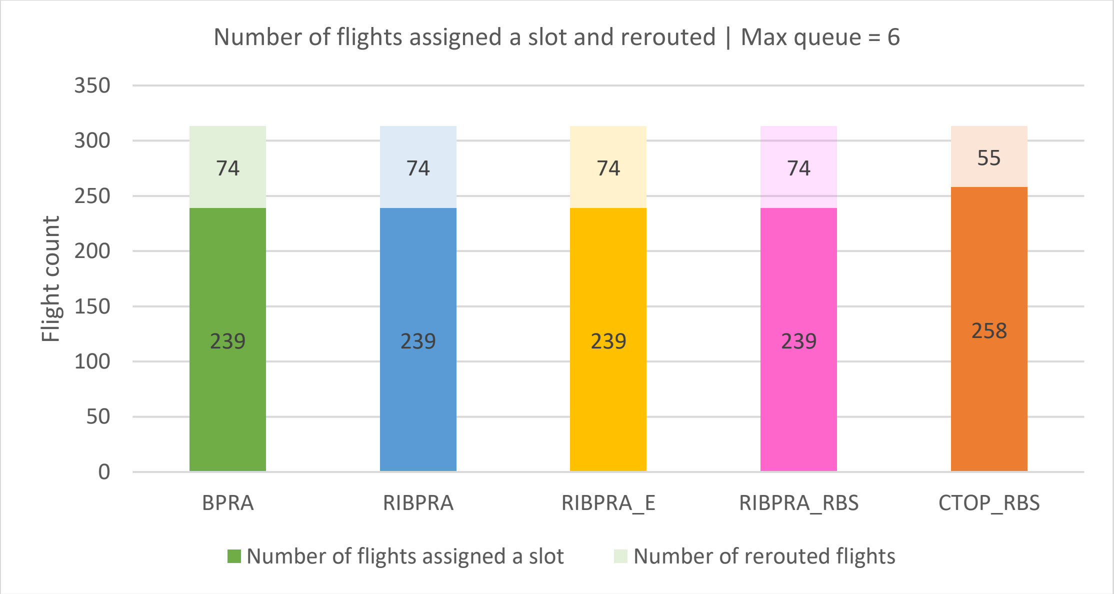


Figure 24: Number of flights assigned a slot and rerouted

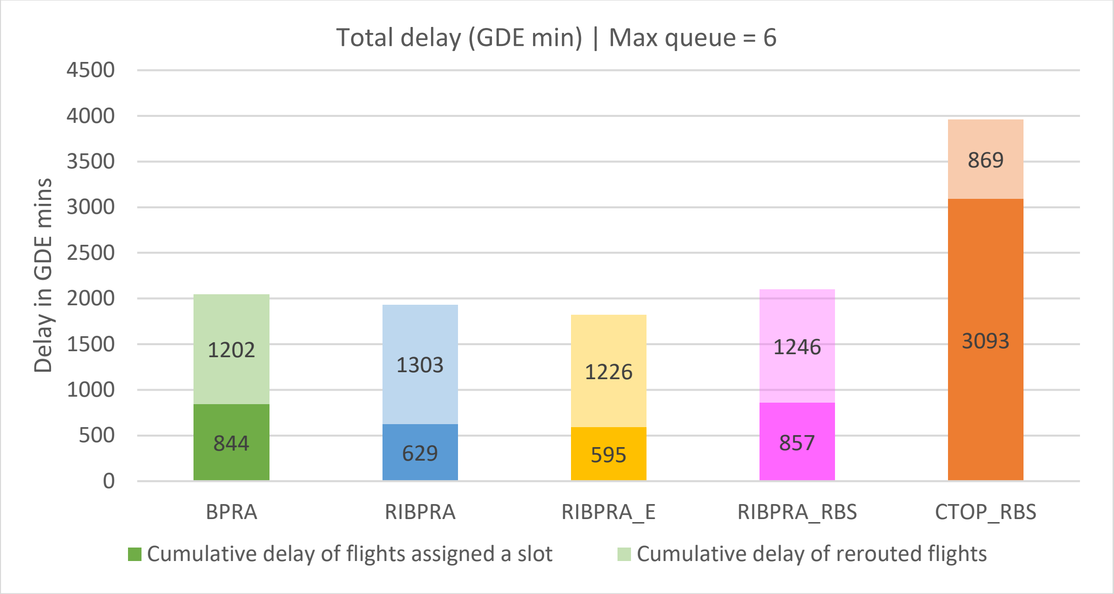


Figure 25: Total delay split over flights assigned a slot and rerouted

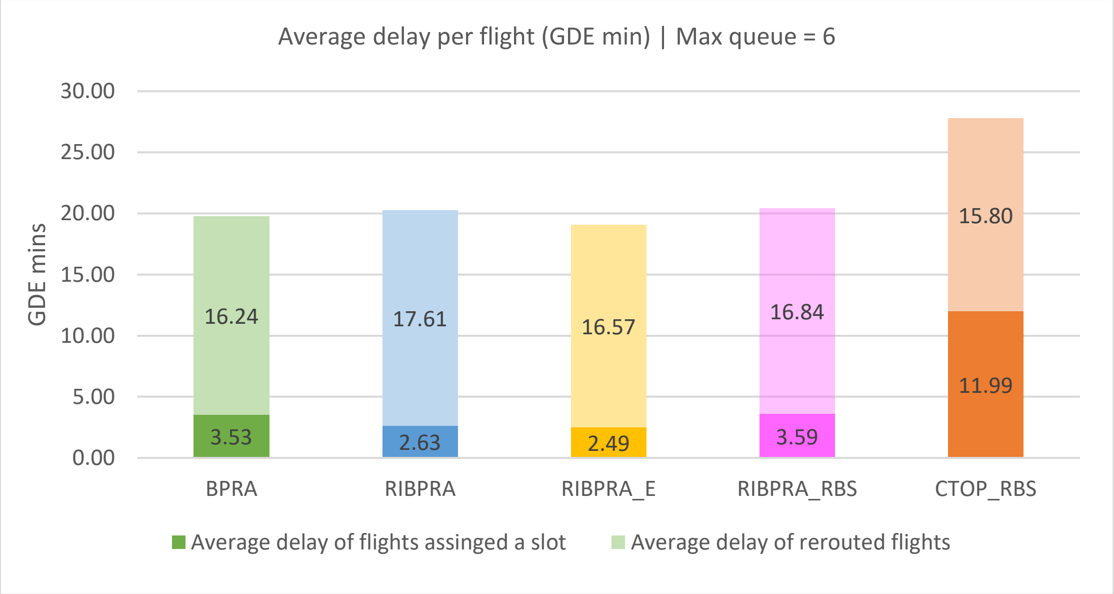


Figure 26: Average delay per flight

In the results displayed so far, all flights are considered “equal” in the sense that a unit of delay to any of the flights is counted equally. However, it was clear from earlier sections that there was some motivation to distinguish flights by the priorities assigned to them by their carriers. As a result, it makes sense to investigate a metric that allows delays to higher priority flights to play a more important role than delays of the same magnitude to lower priority flights. To this end, we introduce a metric called preference weighted delay; it is computed by multiplying the delay for each flight by its preference value. This gives us a measure of how well the allocation schemes allocates delay to the high priority flights and how effectively it ensures that the low priority flights are rerouted/assigned a route option from its TOS. One of the goals with the proposed approaches was to try to subsume the cancellation, substitution, and compression processes that follow RBS in a CDM paradigm. Since BPRA, RIBPRA, RIBPRA_E and RIBPRA_RBS rerouted the same number of flights (Figure 24), the preference weighted delay metric can give us insight into what are the flights that are assigned a slot at the FCA or rerouted.

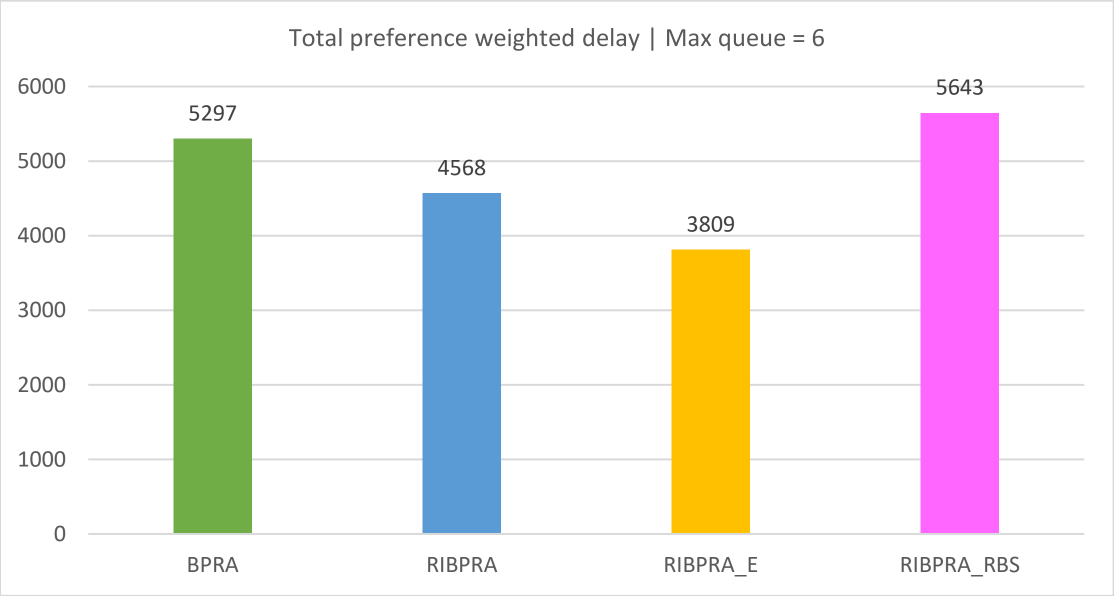


Figure 27: Total preference weighted delay

It is clear from Figure 27 that RIBPRA_E performs better than the other proposed approaches. Figure 28 gives us an insight into how the preference weighted delay is split among the flights assigned a slot and rerouted. Figure 28 also reinforces the result that RIBPRA_E outperforms the other proposed approaches, as it produces the least amount of preference weighted delay to the 239 flights that were assigned a slot and the least amount of cumulative delay on flights that were assigned to a slot (Figure 25 and 26). Apart from that, RIBPRA_E also produces the least amount of preference weighted delay of rerouted flights. It should also be noted that though BPRA produces the least amount of cumulative delay of rerouted flights (Figure 25), RIBPRA performs better than BPRA by ensuring that rerouted flights are of low priority, which can be seen from Figure 28.

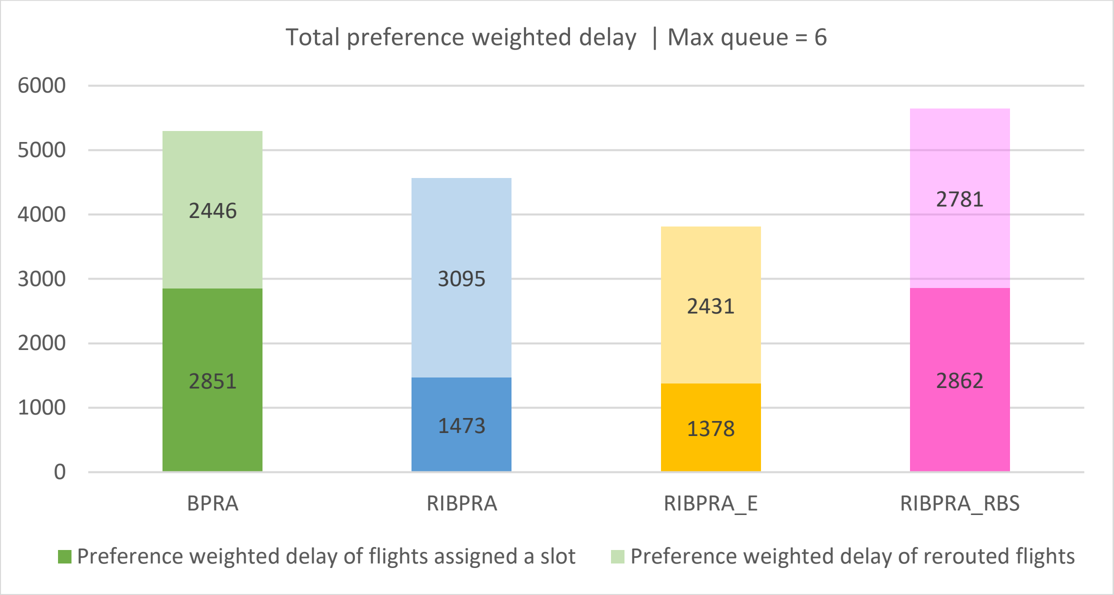


Figure 28: Total preference weighted delay split by flights assigned a slot and rerouted

Another way to study the impact of the stated flight preferences is to measure the average preference of the flights assigned a slot and rerouted. If the preference structure works as intended, then arguably the average preference of flights assigned a slot should be high, as high priority flights should have precedence for slot assignments. Conversely, the average preference of rerouted flights should be (relatively) low. Figure 29 restates the information that RIBPRA_E overshadows the other approaches in overall system efficiency; it has the highest average preference of flights assigned a slot and the least average preference of rerouted flights.

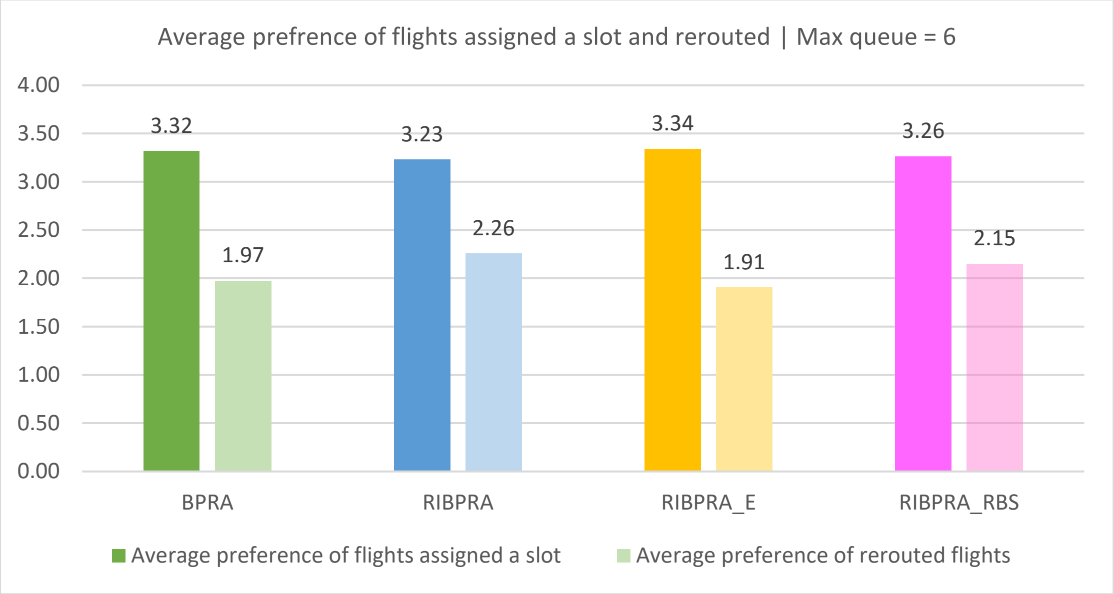


Figure 29: Average preference value of flights assigned a slot and rerouted

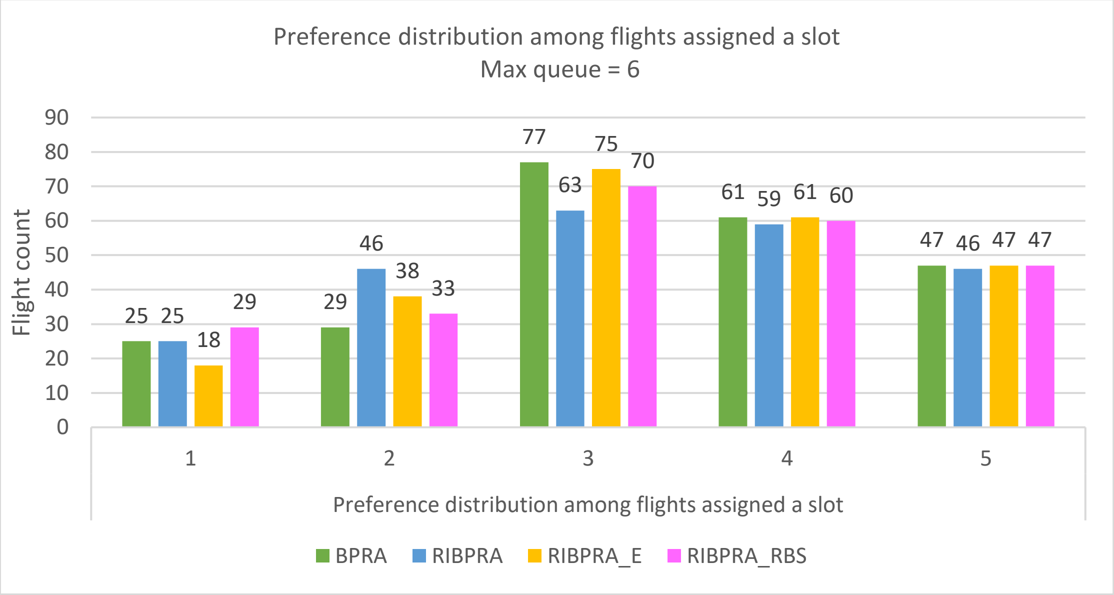


Figure 30: Preference distribution among the flights assigned a slot

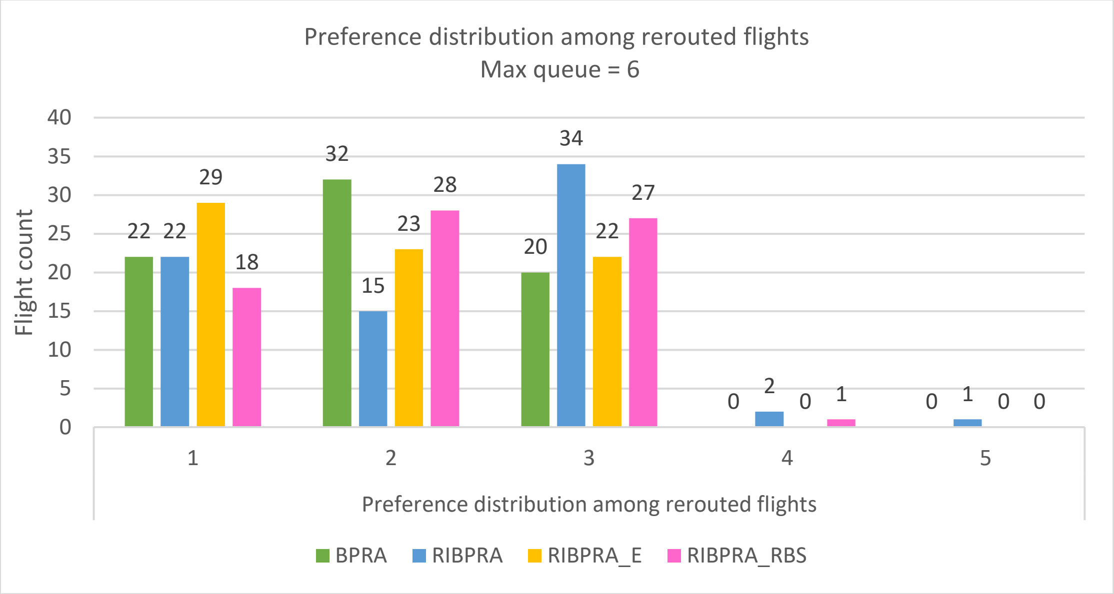


Figure 31: Preference distribution among rerouted flights

Figure 30 and Figure 31 tell us about the preference value distribution among the flights assigned a slot and flights rerouted. It gives the number of flights that were assigned a slot and rerouted, by each of the respective preference values. From Figure 30, we can see that not all flights that were assigned preference value 1 by the corresponding airlines were rerouted; some were assigned a slot. Additionally, the flights that were assigned a preference value 4 or 5 were almost never rerouted. This shows that it is not the case that the allocation method simply reroutes all the flights with the low preference numbers and gives slots to the high priority flights; the truth is more complex, and depends considerably on the parameters of the problem. This property arises due to the consideration of preference value of a flight in the allocation mechanisms. Due to this, airlines might be motivated to express their true priority of flights, as their high priority flights are almost ensured a slot and their low priority flights are not always rerouted.

7.3. Comparison of allocation schemes by participants:

It is not only important that an allocation method reduces total system delay; it is also vital to see its impact on each participant, especially since CTOP falls under the CDM paradigm. The equity factor also cannot be addressed collectively for a system; it needs to be addressed for each participant. From the airline perspective, the CTOP decision process could be considered complex because there are many unknown variables to plan its best possible group of TOS messages, e.g., amount of captured flights of other airlines, demand and capacity rate of each time window, demand of each FCA, strategy used by other airlines to define their TOS, and others. Current solutions for this problem are based on greedy methods, minimizing the total system cost (system as a whole) based on flight-slot assignment (FAA, 2014; and Kim, 2015).

The following airlines/flight operators were considered for the analysis, listed by airline name and ICAO call sign in parentheses:

1. United (UAL)
2. Envoy (ENY)
3. Republic (RPA)
4. Executive Jet Management (EJM)
5. Delta (DAL)
6. Endeavor Air (FLG)
7. Southwest (SWA)
8. Trans States Airlines (LOF)
9. American (AAL)
10. SkyWest Airlines (SKW)
11. Shuttle America (TCF)
12. Atlantic Southeast Airlines (ASQ)
13. Executive Jet Aviation (EJA)

14. Pegasus Elite Aviation (PEG)
15. Jet Logistics (JLG)
16. Air Wisconsin (AWI)
17. Virgin America (VRD)
18. Jet Blue (JBU)
19. Frontier Airlines (FFT)
20. Alaska Airlines (ASA)
21. Horizon Air Charter (NKT)
22. Jetall Holdings (JTL) (Canada)
23. Mesa Airlines (ASH)
24. PSA Airlines (JIA)
25. GoJet Airlines (GJS)
26. XOJET (XOJ)
27. Sunset Aviation (TWY)
28. Priority Aviation Company (NKC)

We would like to mention that there were other airlines/flight operators who had their flights in our experimental CTOP test case scenario. There were 33 other flight operators who each had a flight in the CTOP test case scenario but displaying results for a total of 55 participants where more than 65% of the participants displayed a similar property adds to the redundancy of the results and makes an unwieldy presentation. These airlines/flight operators were not excluded from our experiment; we will simply not be presenting their results here. We believe that the 28 listed participants have captured the unique properties displayed by all the participants.

Figure 32 shows the Total delay incurred by the flight operators for the allocation schemes, CTOP_RBS, BPRA, RIBPRA, RIBPRA_E and RIBPRA_RBS. The proposed allocation reduces the total delay of all the flight operators irrespective of the number of flights each have in the test case scenario.

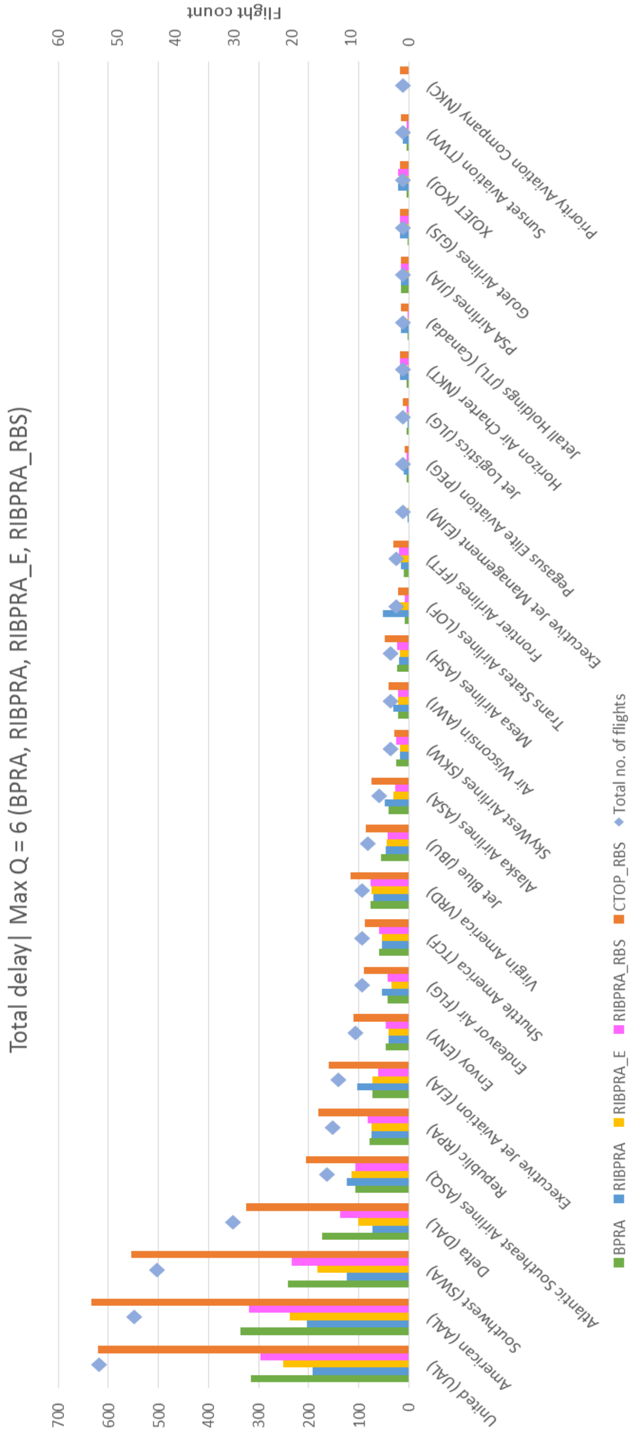


Figure 32: Total delay by flight operators

The cumulative delay of flights assigned a slot and flights rerouted are shown in Figure 33. The figure shows how the total delay is absorbed among the flights assigned a slot and rerouted flights. It can be seen from Figures 32, 33, and 34 that the flight operator Trans States Airlines (LOF) is heavily penalized in the allocation scheme RIBPRA, larger than what it experienced in CTOP_RBS, which was due to the nature of RIBPRA, whereby it provides a significant advantage to flight operators who have a larger percentage of flights over the flight operators who have lesser percentage. This nature of RIBPRA was expected, which motivated us to refine the allocation scheme, and as a result RIBPRA_E and RIBPRA_RBS were developed. The BPRA, RIBPRA_E and RIBPRA_RBS methods reduced the delay experienced by Tran State Airlines (LOF) significantly when compared to the amount of delay the flight operator experienced under CTOP_RBS and RIBPRA. Figures 35, 36, and 37 reiterate this fact. However, the performance superiority of the proposed allocation approaches over CTOP_RBS is absolute, apart from the one flaw in RIBPRA.

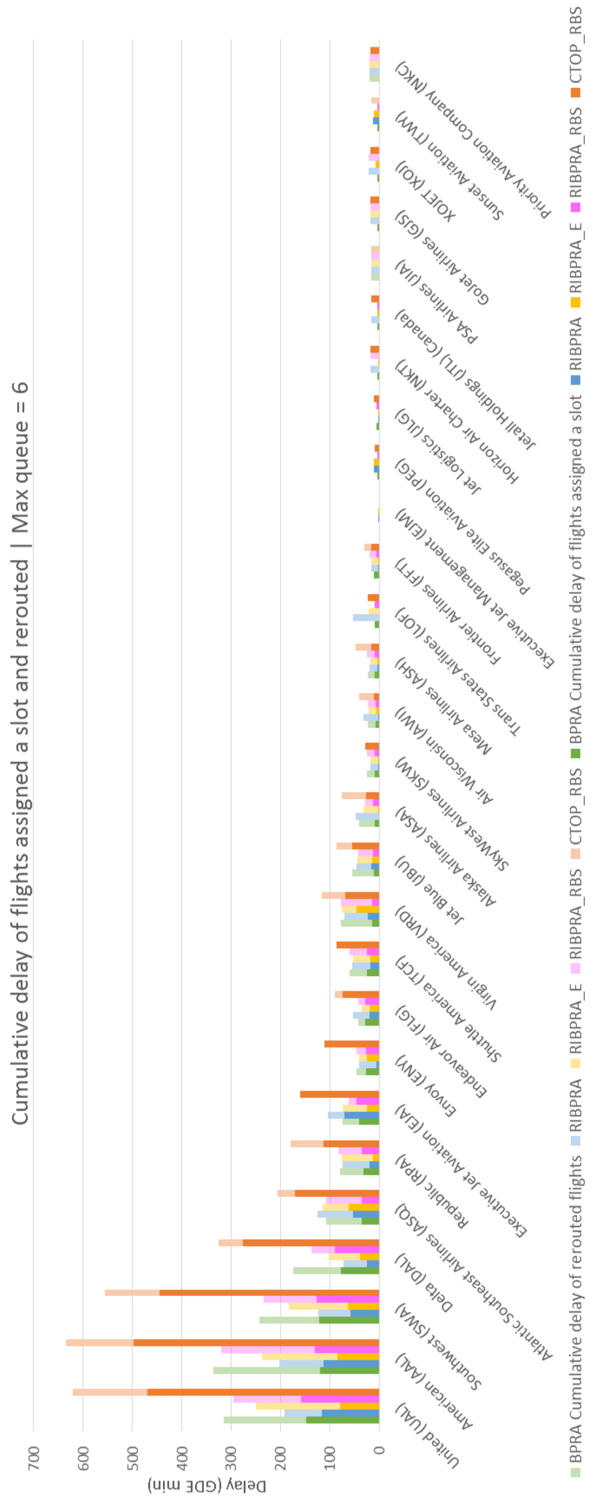


Figure 33: Cumulative delay of flights assigned a slot and rerouted by flight operators

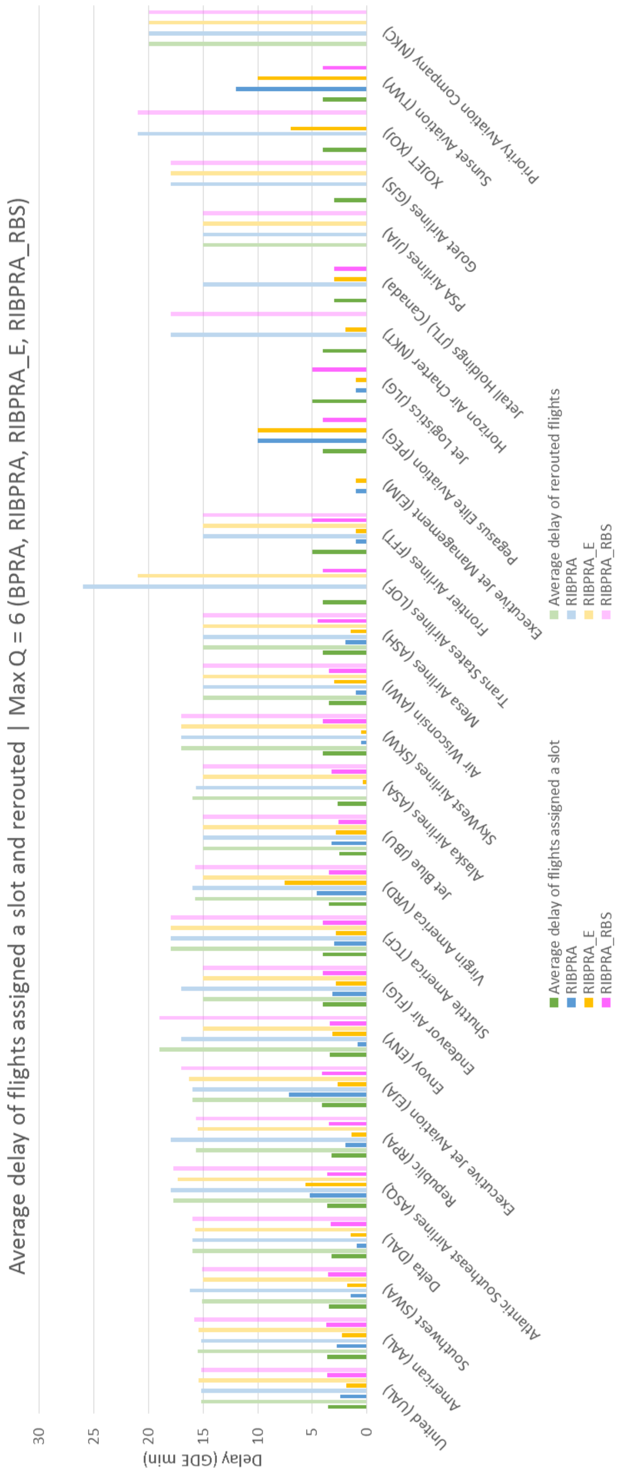


Figure 34: Average delay of flights assigned a slot and rerouted by flight operators

Total preference weighted delay, and the distribution of preference weighted delay among the flights assigned a slot and rerouted gives us insight into how effectively the proposed allocation schemes make the allocation of slots to flights and handles the rerouting decision for each participant (Figures 35, 36, and 37). Among BPRA, RIBPRA, RIBPRA_E, and RIBPRA_RBS, RIBPRA_E does the allocation and rerouting better than the other methods, as it significantly reduces the preference weighted delay in comparison to BPRA and RIBPRA_RBS. RIBPRA marginally outperforms the RIBPRA_E only for airlines/flight operators who have a higher percentage of flights in the test case scenario. RIBPRA_E ensures that there is no disparity between the airlines. RIBPRA_E reduces the delay assigned to the airlines that have a lower percentage of lights in comparison to RIBPRA (Figure 35, 36, and 37).

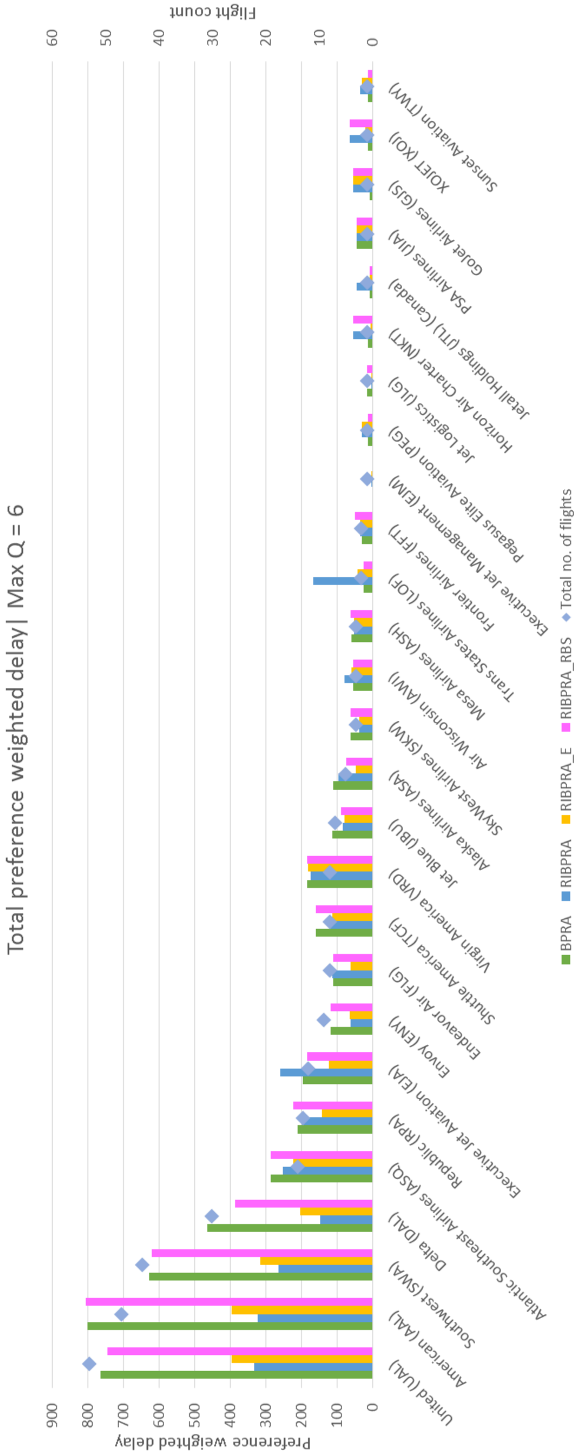


Figure 35: Total preference weighted delay by flight operators

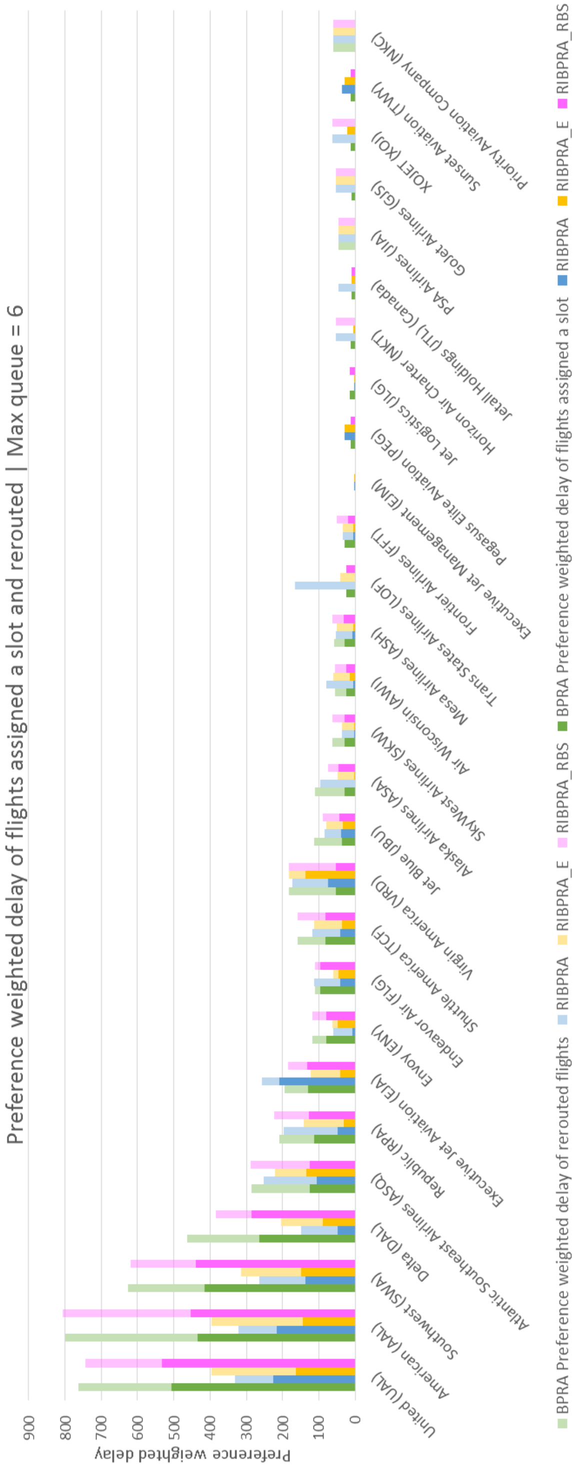


Figure 36: Preference weighted delay of flights assigned a slot and rerouted by flight operators

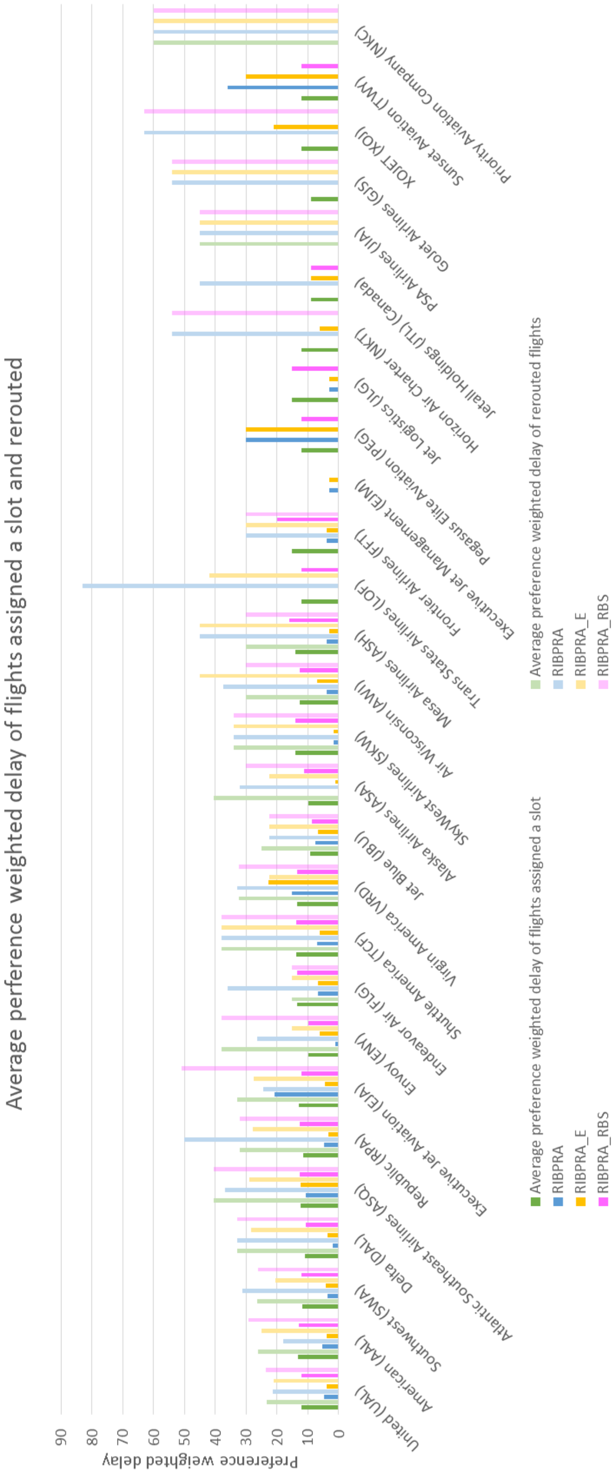


Figure 37: Average preference weighted delay of flights assigned a slot and rerouted by flight operators

Recall that another metric that identifies how effectively the allocation processes assigns delay to the flights is the average preference of flights assigned a slot and rerouted. Figures 38,39, and 40 illustrate that the average preference of flights assigned a slot under RIBPRA_E is higher than the other allocation methods except for a few airlines (Figure 39) but it is important to note that it reroutes the least average preference of rerouted flights for these airlines (Figure 40).

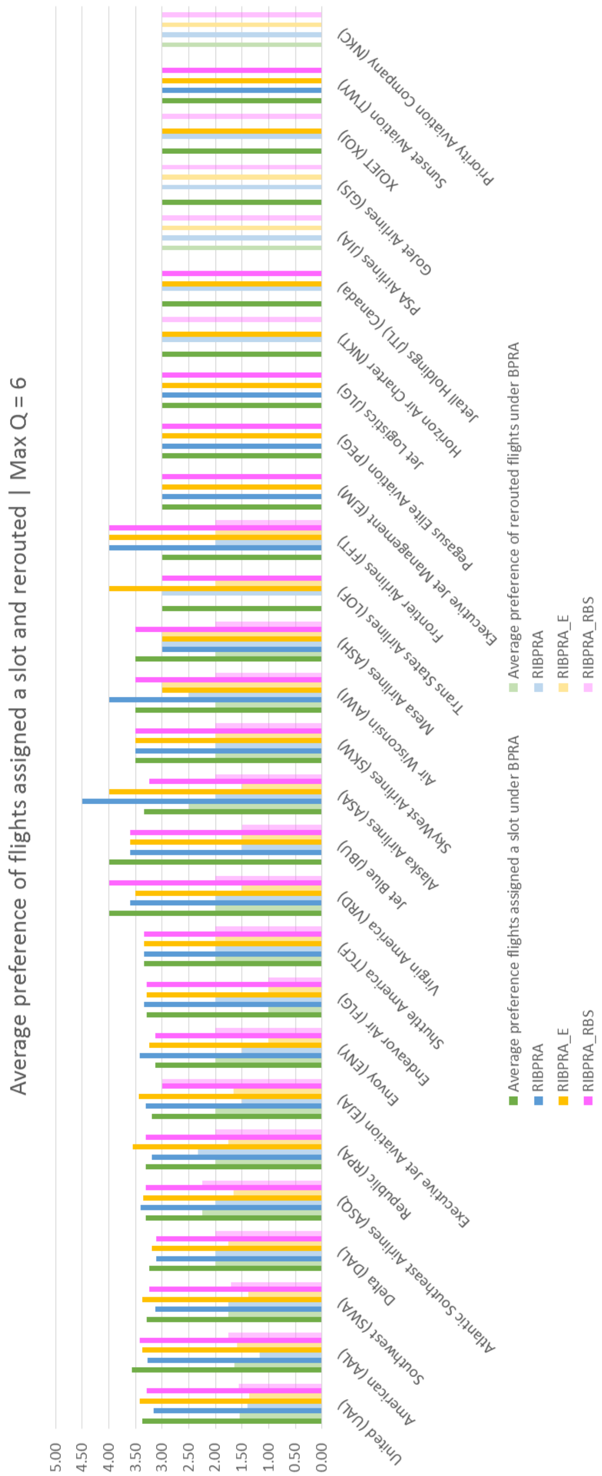


Figure 38: Average preference of flights assigned a slot and rerouted by flight operators

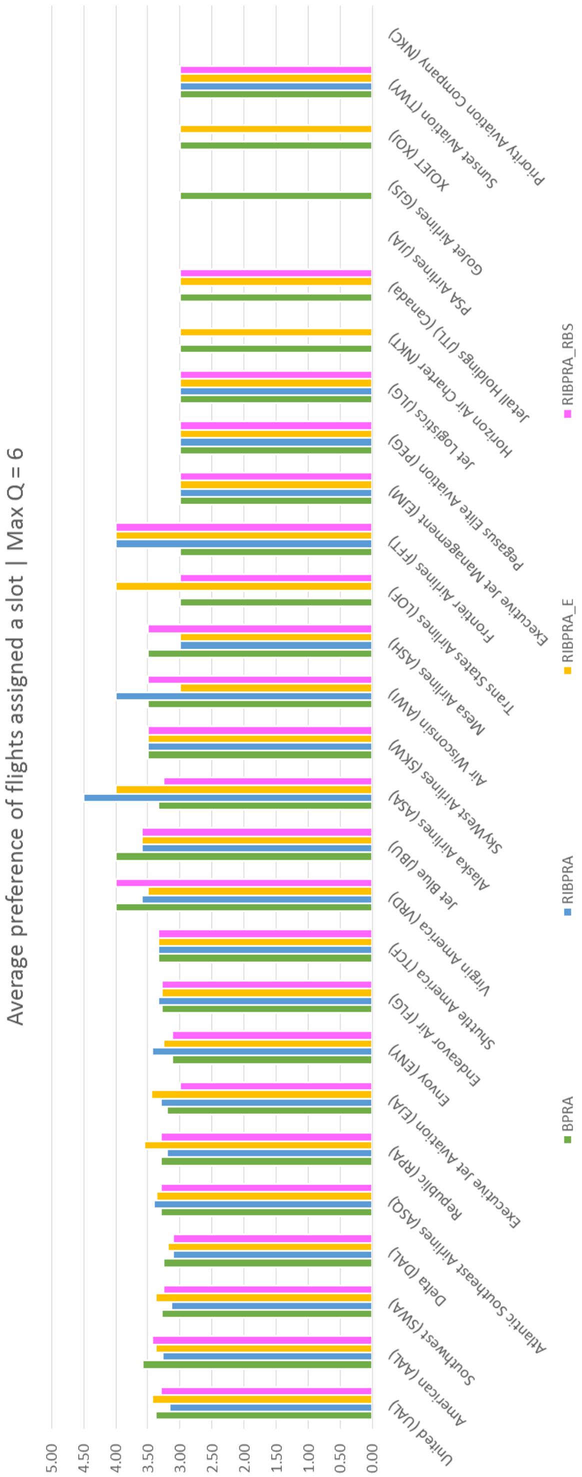


Figure 39: Average preference of flights assigned a slot by flight operators

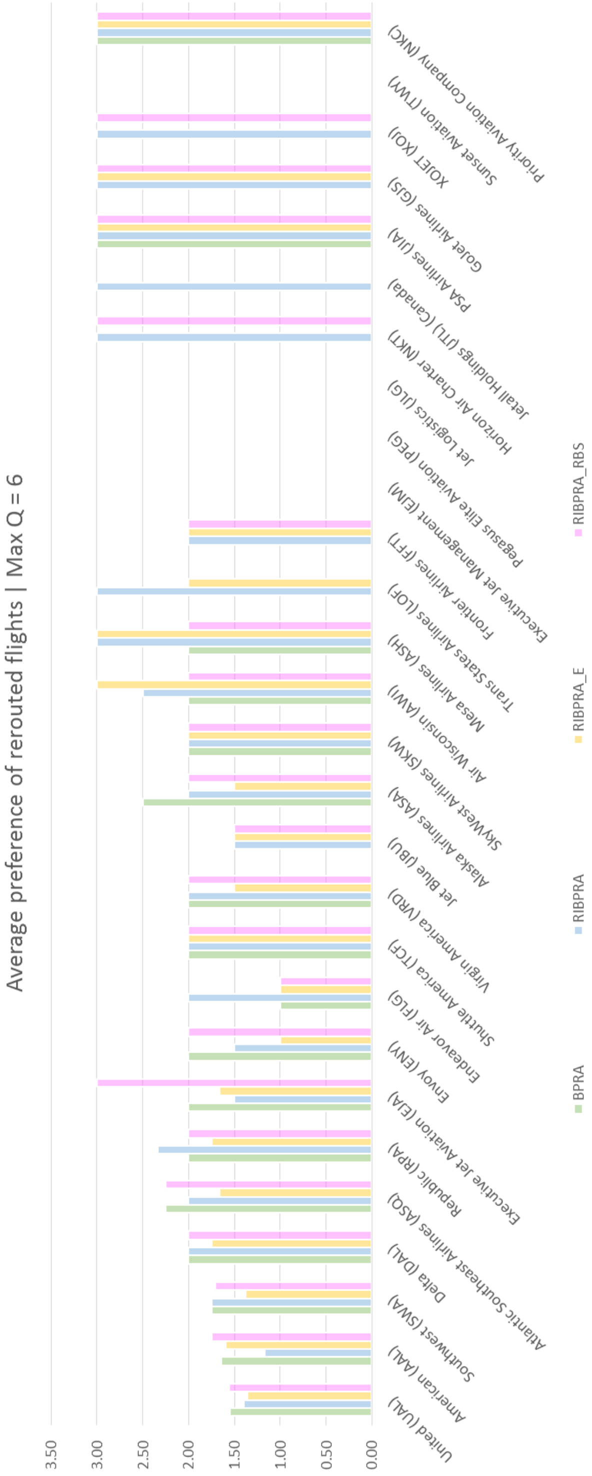


Figure 40: Average preference of rerouted flights by flight operators

Equity concerns are always predominant among the airlines in the face of an allocation scheme as there are concerns of “gaming” the system issue in a CTOP (Evans et al., 2014; Bosung et al., 2014; Hoffman et al., 2003; and Cruciol et al., 2015), which reiterates the importance of equity metrics. As mentioned in Section 5.4 there are several equity criteria (Wanke et al., 2006) which can be considered but no one of them is universally accepted. We will be using the metric *fair share* (Pourtaklo and Ball, 2009) as a comparison metric. The fair share of each airline/ flight operator is based on the initial arrival time FCA of flights. A flight operator's fair share is interpreted as the number of slots the carrier should receive. Fair share assignment meets equity principles such as impartiality, equal treatment of equals, consistency, and demand monotonicity. For a detailed description of fair share the reader is referred to Pourtaklo and Ball (2009).

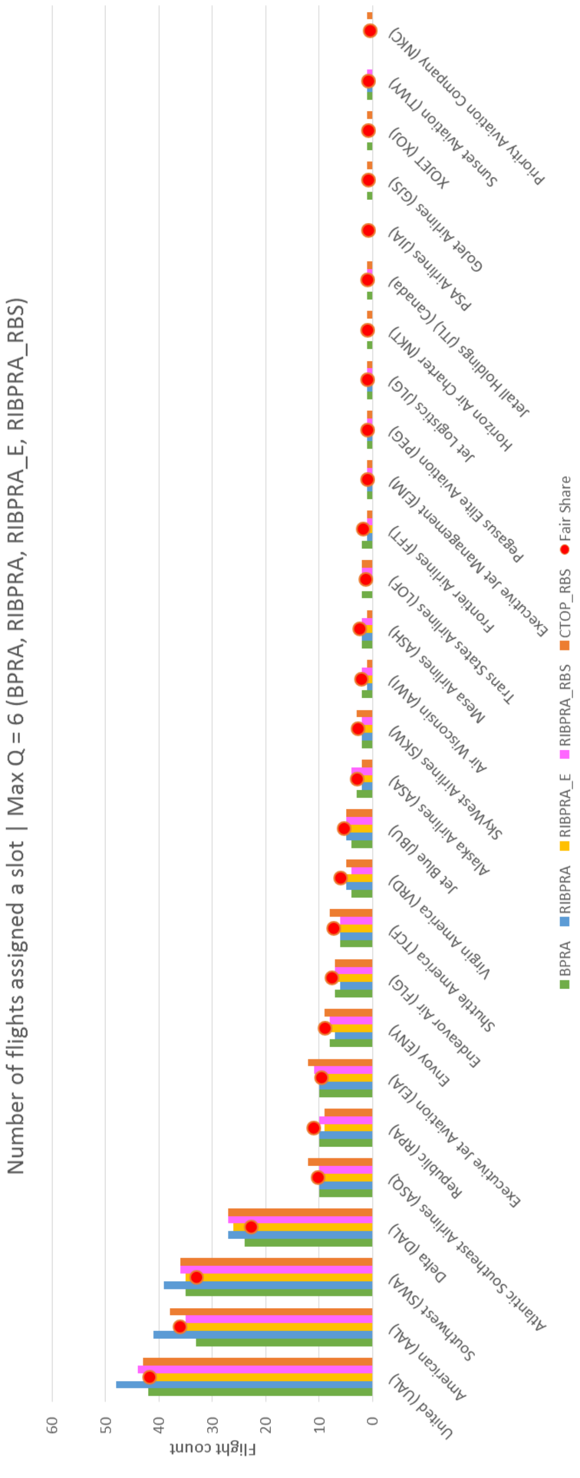


Figure 41: Comparison of number of flights assigned to airlines allocation approaches and Fair share

The airlines received more slots under CTOP_RBS than BPRA, RIBPRA, and RIBPRA_RBS (Figure 41) but this is merely due to the fact that our proposed allocation methods reroute more flights (Figure 24) since these methods are based on a common principle that by creating a small queue, and rerouting a percentage of incoming flights so that the queue does not increase in size (maintaining the queue size within a fixed value), thereby reduces the total delay. The number of slots received by the airlines under the proposed allocations is close to their fair share value (Figures 41 and 45). It is vital to understand that the fair share value calculated for an airline is not necessarily an integral value.

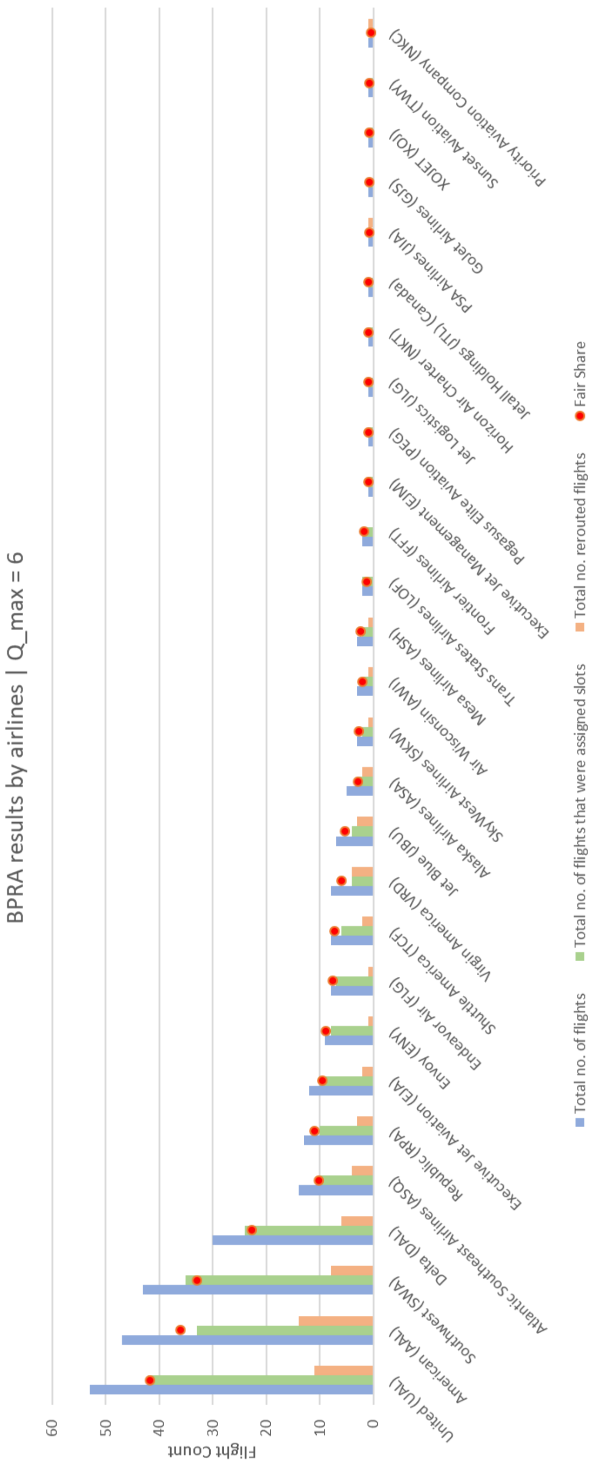


Figure 42: High level results of BPRA by flight operators

Figure 43: High level results of RIBPRA by flight operators

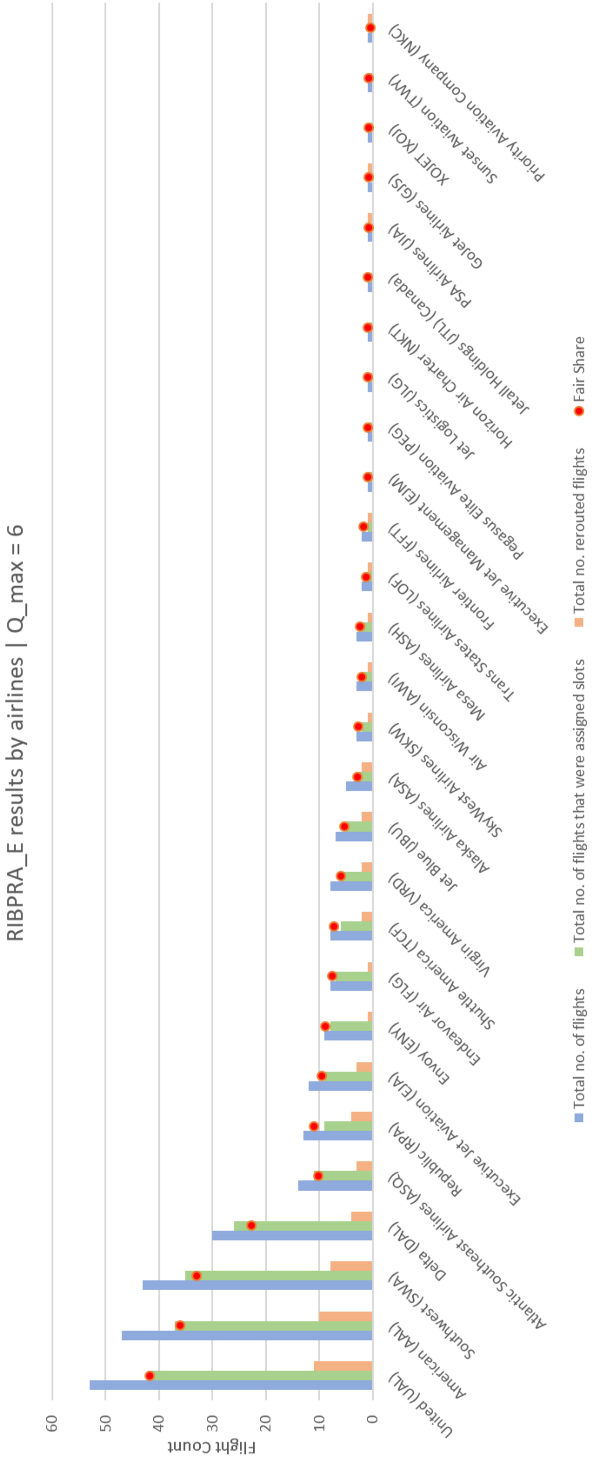


Figure 44: High level results of RIBPRA_E by flight operators

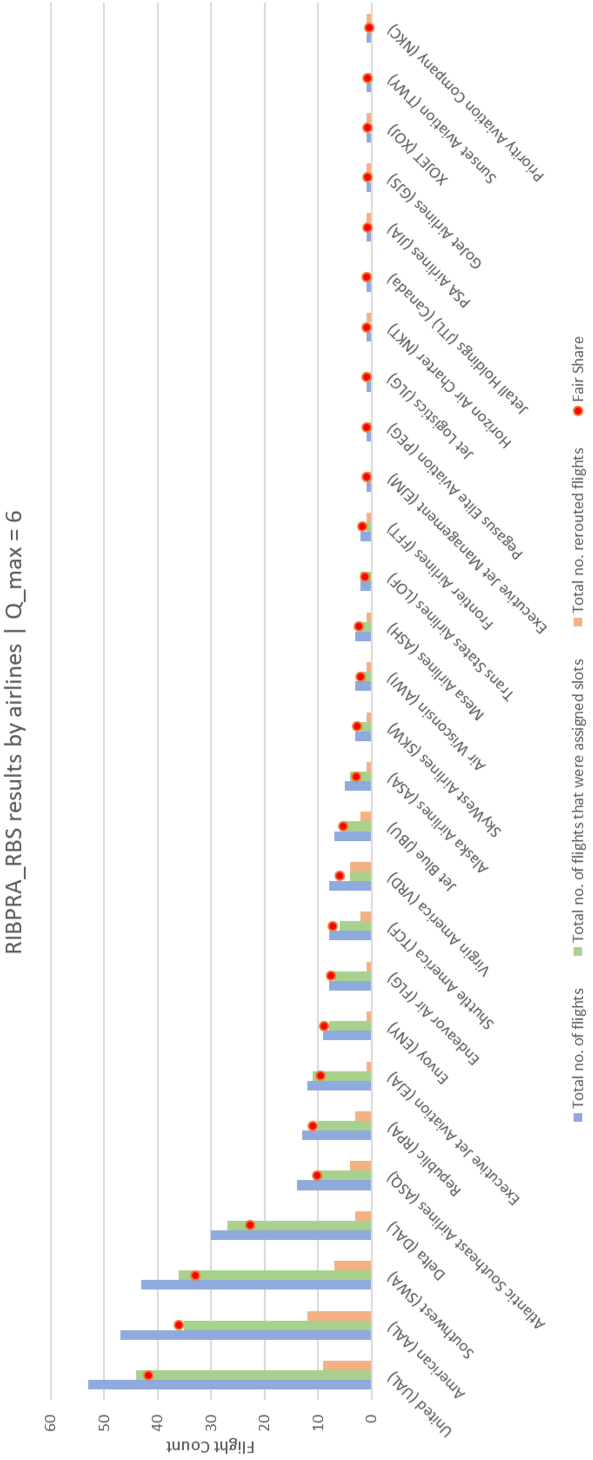


Figure 45: High level results of RIBPRA_RBS by flight operators

The flaw in the proposed allocation method RIBPRA is again highlighted here in Figure 43. It can be seen that RIBPRA allocates more slots to carriers who have a higher percentage of flights. The number of slots the airlines received under BPRA, RIBPRA_E and RIBPRA_RBS is remarkably close (Figures 42, 44, and 45) to the fair share. RIBPRA_E only marginally distributes slots better among flight operators when compared to RIBPRA_RBS and BPRA. RIBPRA_RBS and BPRA also allocate slot purely based on the initial arrival time (IAT) of flights at the FCA, implementing the FCFS principle used in the RBS policy, which is considered to be equitable by the FAA and flight operators (Ball et al., 2005; Hoffman et al., 2005; Ball et al., 2010; Jakobovits et al., 2005; and Burke, 2002). However, the rerouting mechanisms and conditions in both the allocation schemes is different.

7.4. *Varying the maximum queue size (Q_max):*

It is easy to see that maximum queue size (Q_max) affects the number of flights getting rerouted, so changing the Q_max in the proposed approaches will have an effect in the performance of the proposed approaches. We vary the maximum queue from 1 to 21 to see its impact over the metrics. The number 21 was chosen as the upper limit since it was the maximum queue size recorded in the CTOP_RBS allocation. Limiting the maximum queue size has a system efficiency and equity trade off, and the maximum queue size also depends on the FCA capacity.

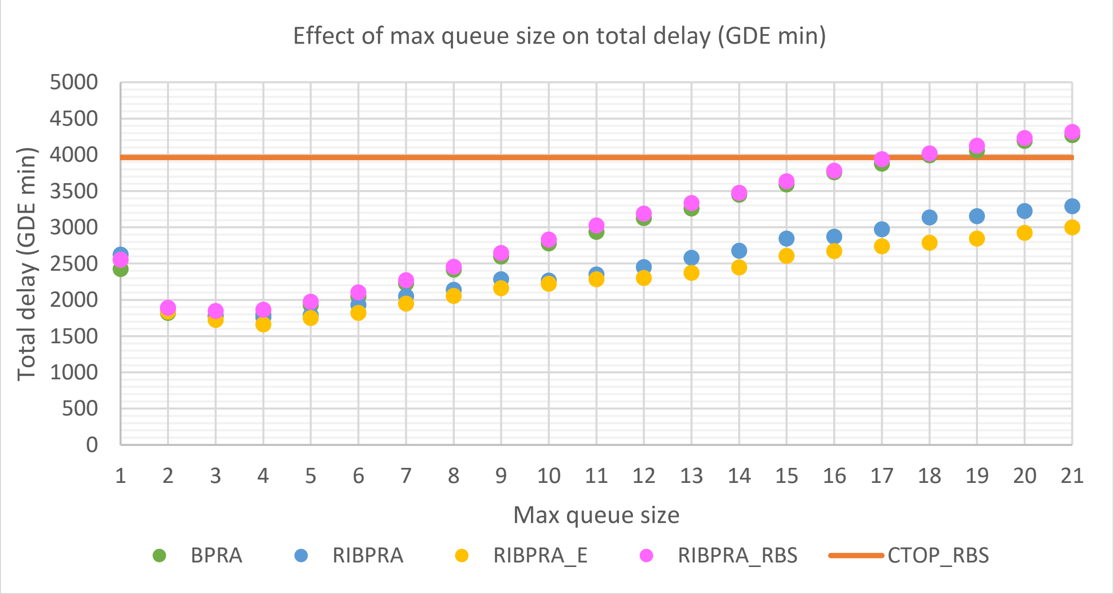


Figure 46: Effect of varying max queue size on total delay

Figures 46 and 47 illustrate the impact of varying the maximum queue size on the total delay. When the maximum queue size is set to 1, the total delay is purely due to the flights rerouted and the flights assigned a slot receive no delay (Figures 47 and 52). When the maximum queue size is 21, the number of flights assigned a slot and rerouted by the proposed allocation methods is the same as the CTOP_RBS. However, RIBPRA_E and RIBPRA are more efficient in reducing the total delay this is due to the difference in the way the flights are assigned a slot and rerouted. Since in RIBPRA and RIBPRA_E a flight is assigned to a slot or rerouted based on the preference value (priority order) indicated by their corresponding airlines. This to a certain extent reduces the need for slot substitutions and cancellations by the airlines due to the fact that there are fewer holes formed in the system (the slots that have no flights assigned to them) thereby alleviating the necessity of a compression process to optimize the slot allocation. It is important to note here that the above result is only valid if the true priority of the flights was conveyed by the preference values assigned by the respective airlines. This result shows that the proposed allocation methods are robust in the sense that they capture the effect of cancellations, substitutions, and compression within them to some extent. This property of RIBPRA and RIBPRA_E could motivate the airlines to provide the true priority among its flights. The performance efficiency of BPRA, RIBPRA, RIBPRA_E and RIBPRA_RBS is degraded when the maximum queue size is set to a large value (Figure 46, 47, 54, and 55). It is because the flights are now made to wait for longer period before the slot assignment and rerouting mechanisms are initiated.

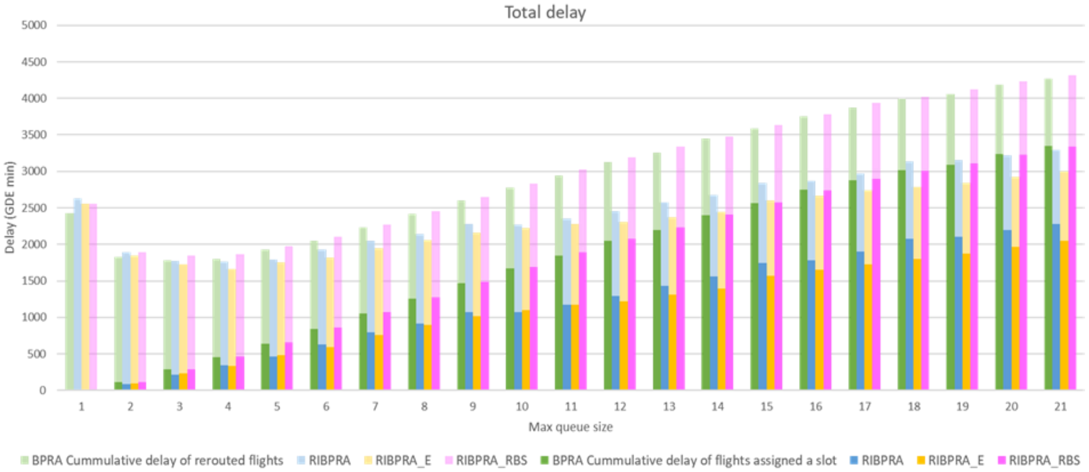


Figure 47: Effect of varying max queue size on cumulative delay of flights rerouted and assigned a slot

The effect on total delay and how the delay is split between the flights assigned a slot and rerouted as result of varying the Q_max for the proposed allocation methods is shown in Figure 48, 49, 50 and 51.

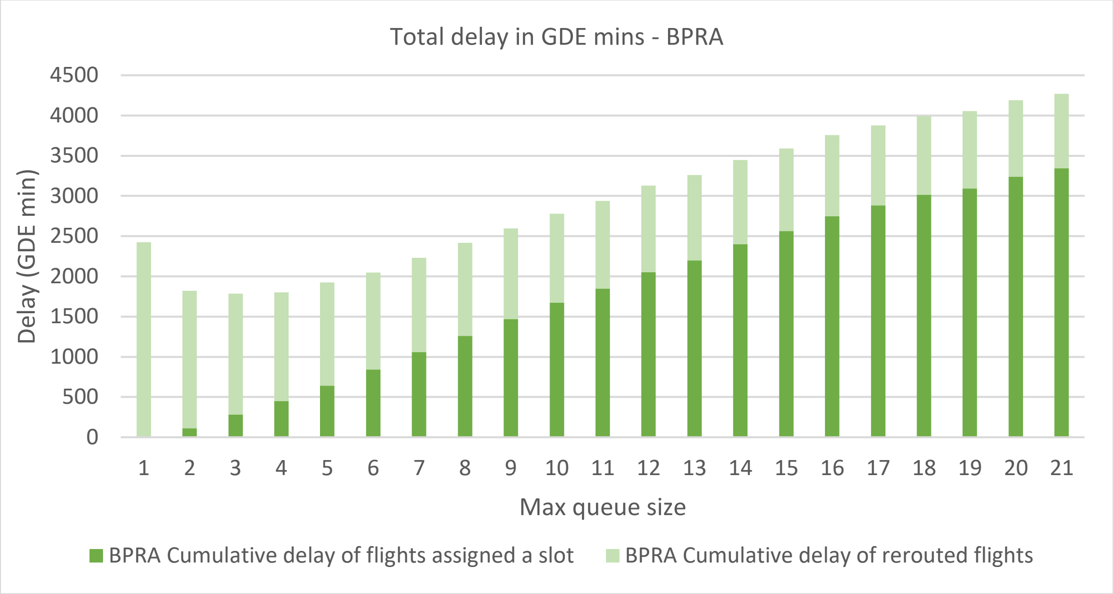


Figure 48: Effect of varying max queue size on total delay, BPRA

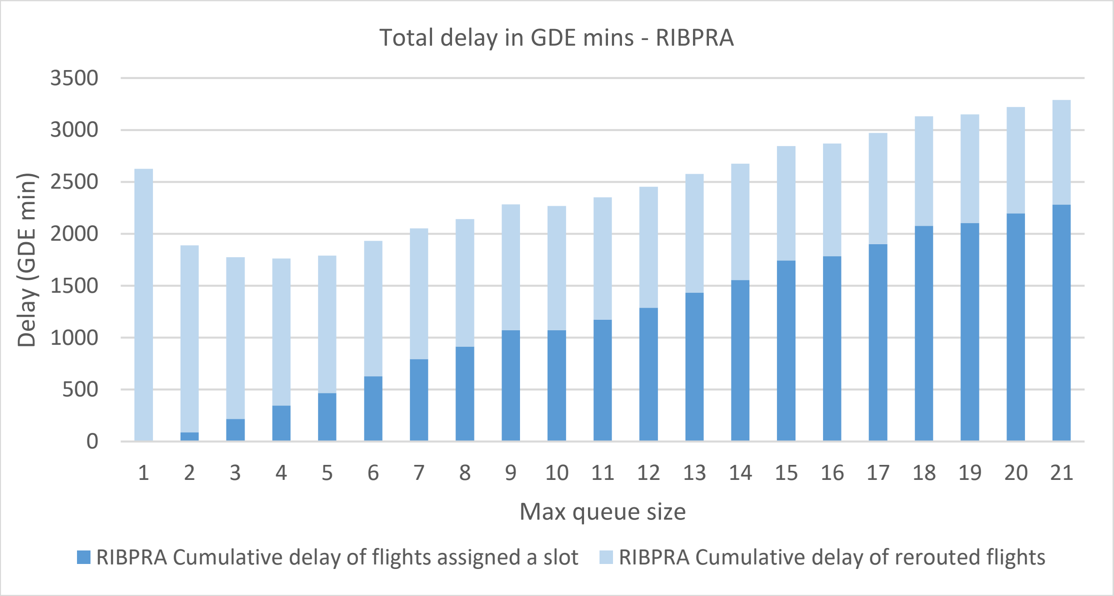


Figure 49: Effect of varying max queue size on total delay, RIBPRA

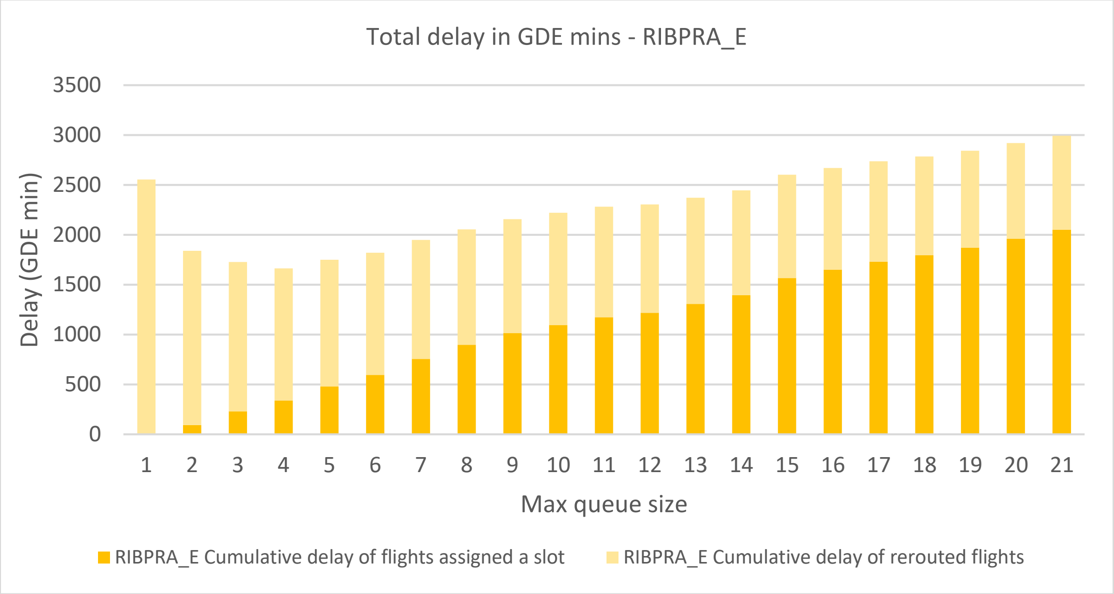


Figure 50: Effect of varying max queue size on total delay, RIBPRA_E

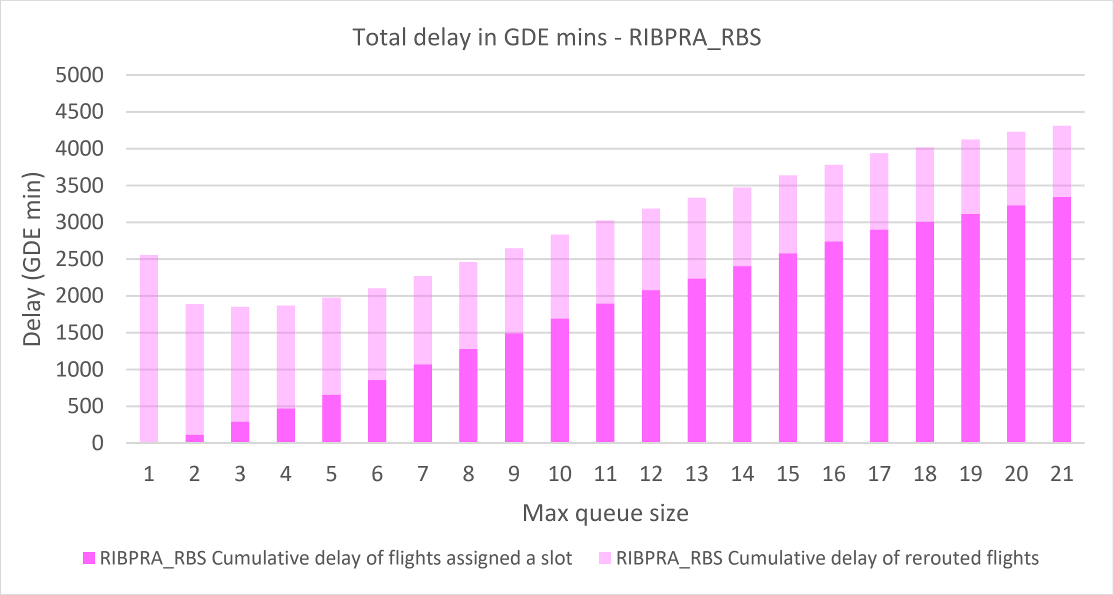


Figure 51: Effect of varying max queue size on total delay, RIBPRA_RBS

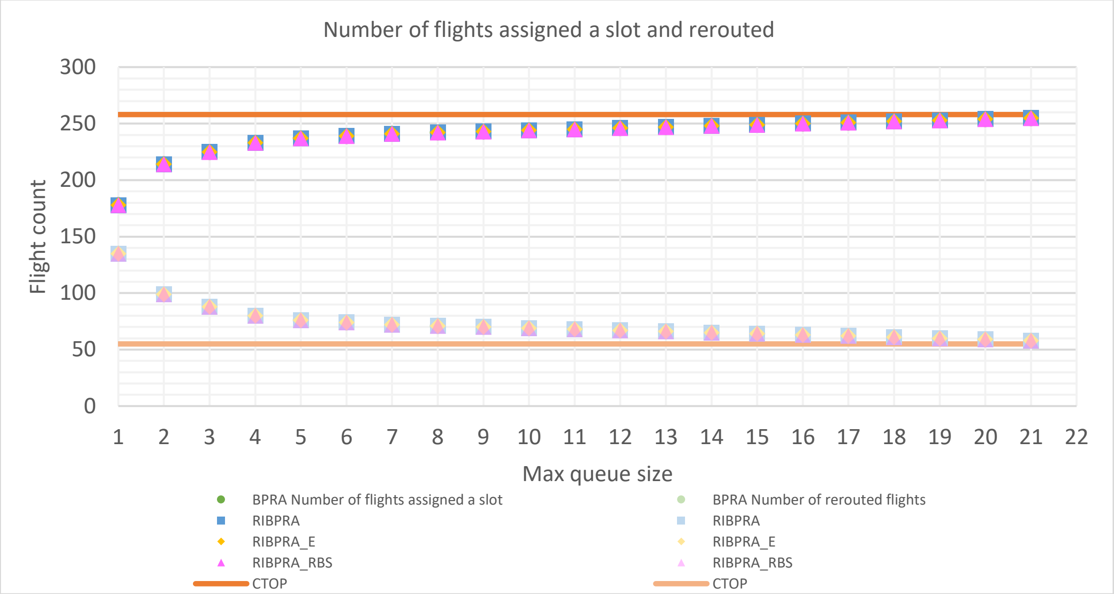


Figure 52: Number of flights assigned a slot and rerouted by max queue size

The number of flights assigned a slot and rerouted depends on the Q_max chosen (Figure 52, and 53), due to the nature of the allocation mechanism. The number of rerouted flights increases as the Q_max in the allocation methods is decreased.

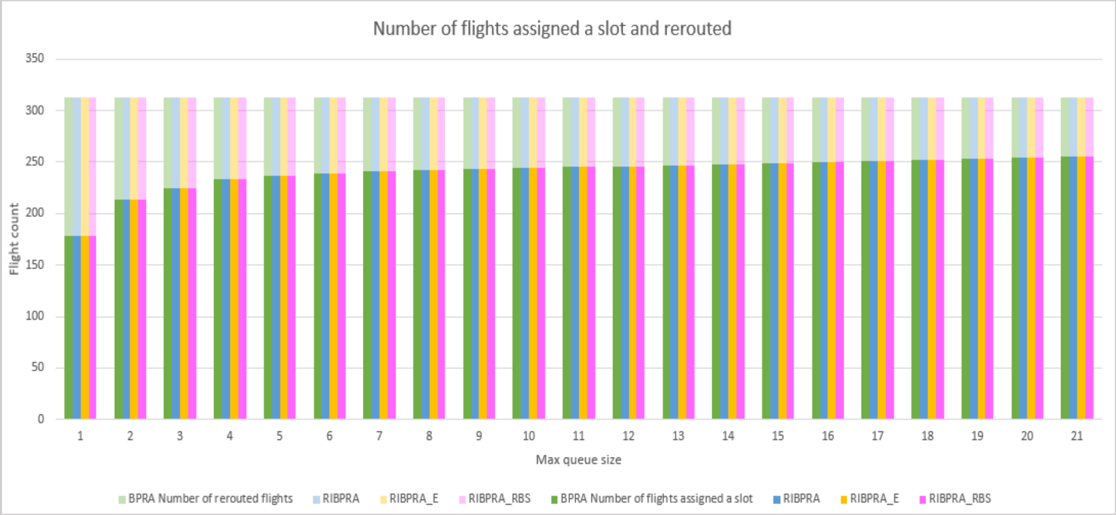


Figure 53: Number of flights assigned a slot and rerouted by max queue size

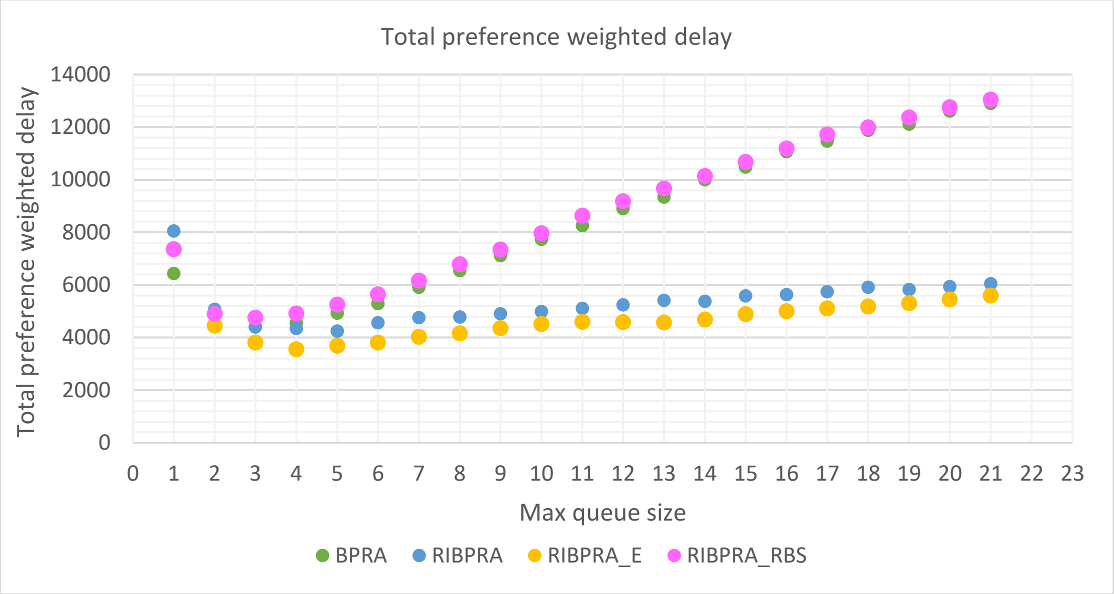


Figure 54: Effect of varying max queue size on preference weighed delay

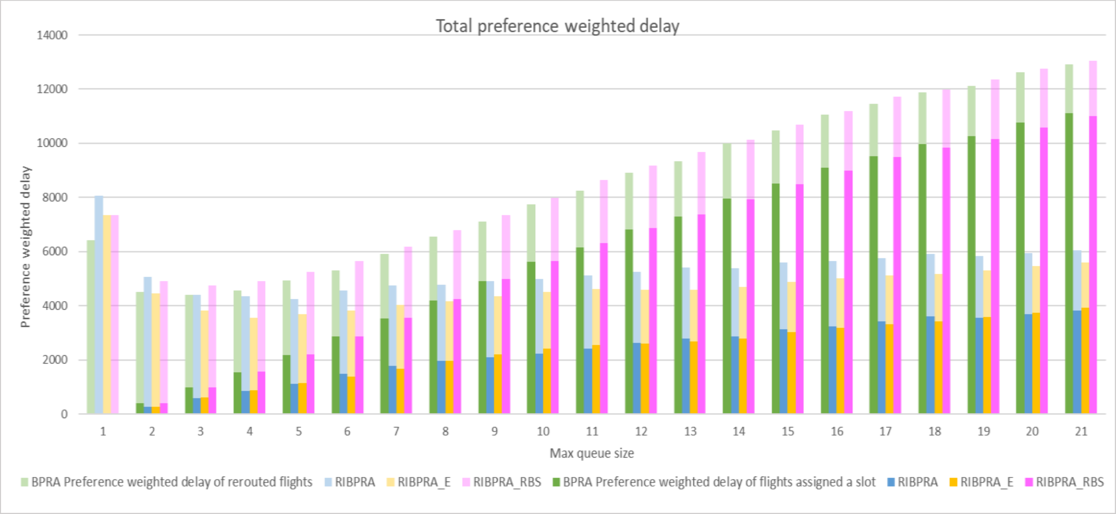


Figure 55: Effect of varying max queue size on preference weighed delay of flights assigned a slot and rerouted

The impact of varying Q_max among the proposed allocation method is shown in Figures 54 and 55. The impact of setting Q_max to a large value is felt heavily by BPRA and RIBPRA_RBS. The effect on total preference weighted delay, and how the delay is split between the flights assigned a slot and rerouted as result of varying the Q_max for the proposed allocation methods is displayed in Figures 56, 57, 58, and 59.

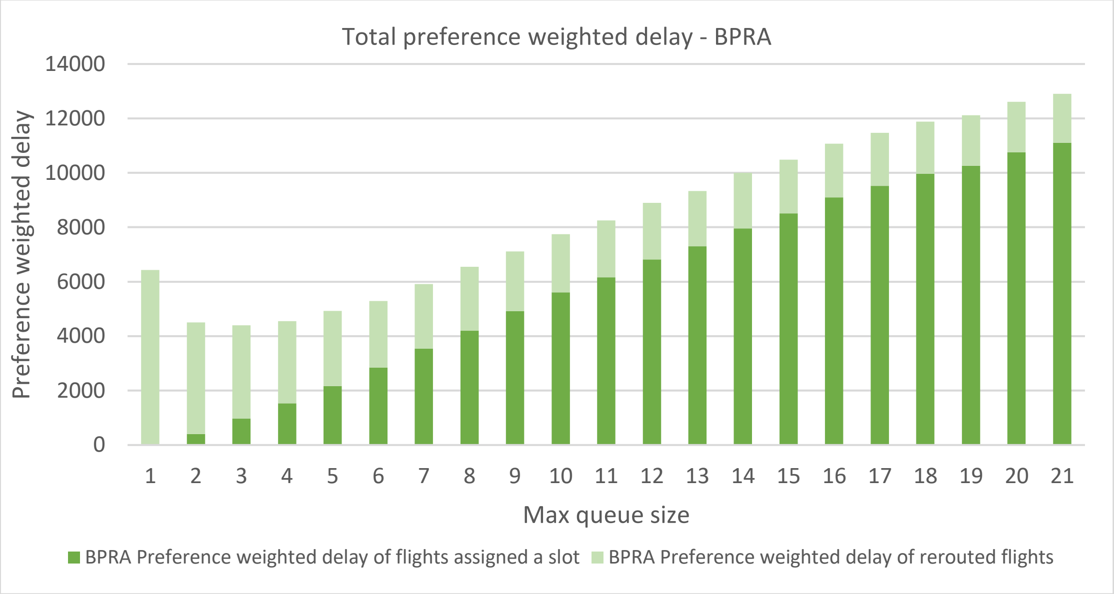


Figure 56: Effect of varying max queue size on preference weighed delay, BPRA

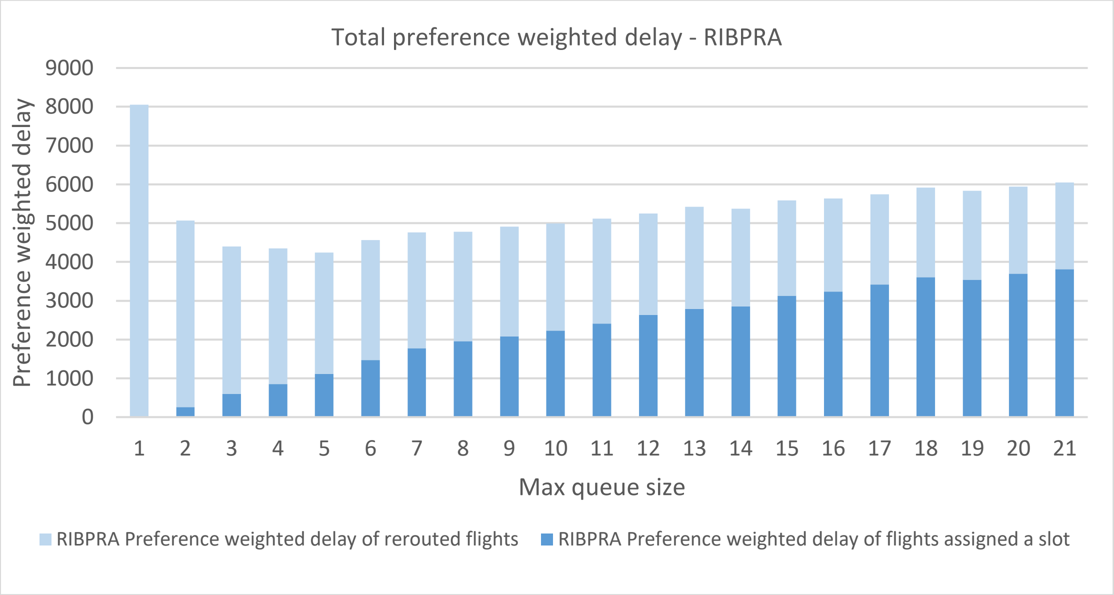


Figure 57: Effect of varying max queue size on preference weighed delay, RIBPRA

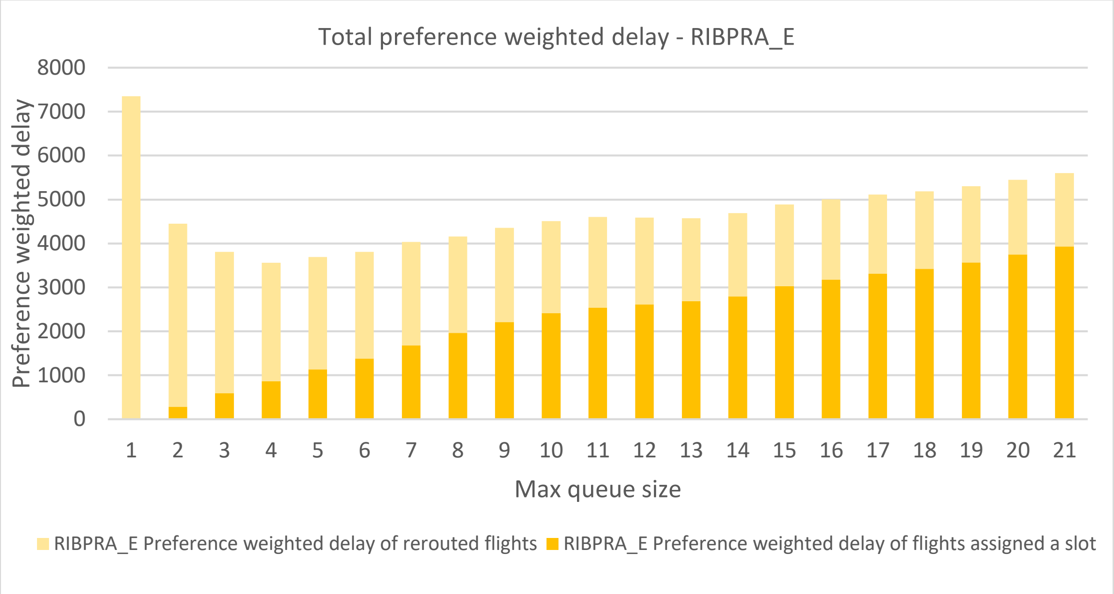


Figure 58: Effect of varying max queue size on preference weighed delay, RIBPRA_E

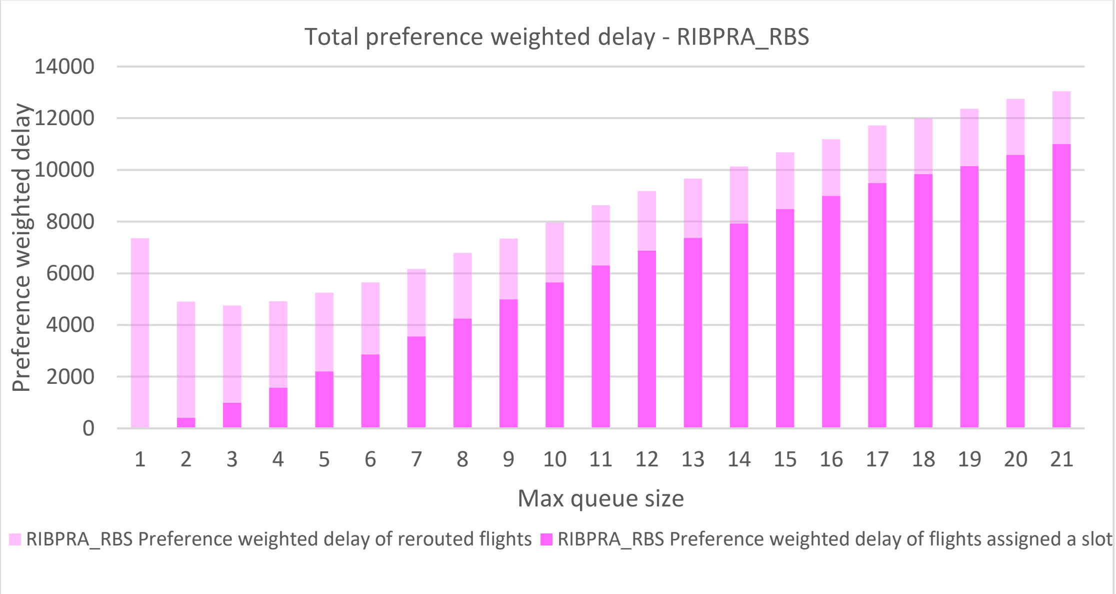


Figure 59: Effect of varying max queue size on preference weighed delay, RIBPRA_RBS

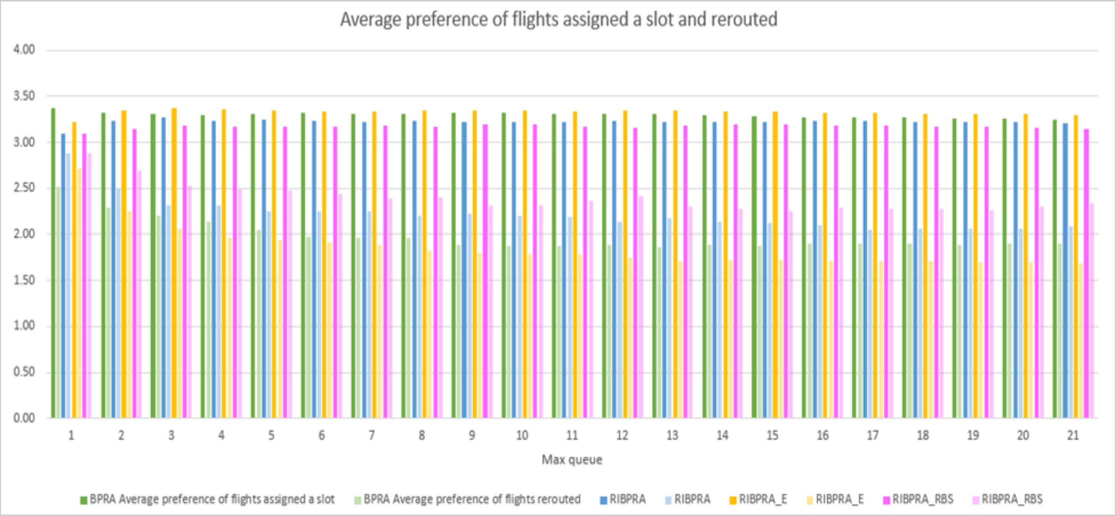


Figure 60: Average preference of flights assigned a slot and rerouted by max queue

As we vary Q_max, the set of flights assigned a slot and rerouted depends on two factors, Q_max and the type of allocation method deployed. RIBPRA_E does perform better among the proposed allocation methods in assigning slots to the flights that have high preference values, irrespective of Q_max, except when Q_max is set to zero (Figures 60, 61, and 61).

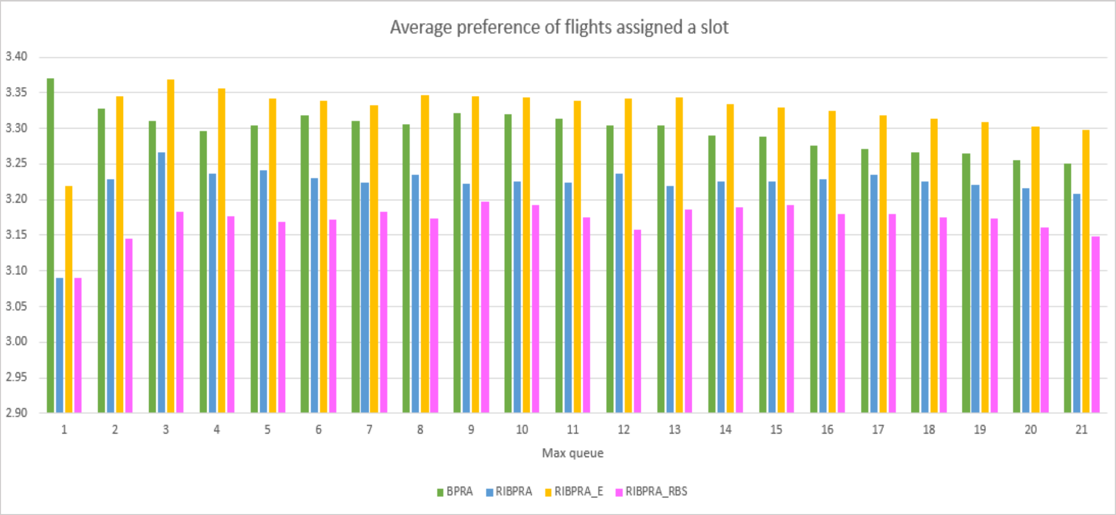


Figure 61: Average preference of flights assigned a slot by max queue

It can also be inferred that RIBPRA_E does perform better among the proposed allocation methods in rerouting the flights that have low preference values irrespective of Q_max, except when Q_max is set to zero (Figures 60, 61, and 62).

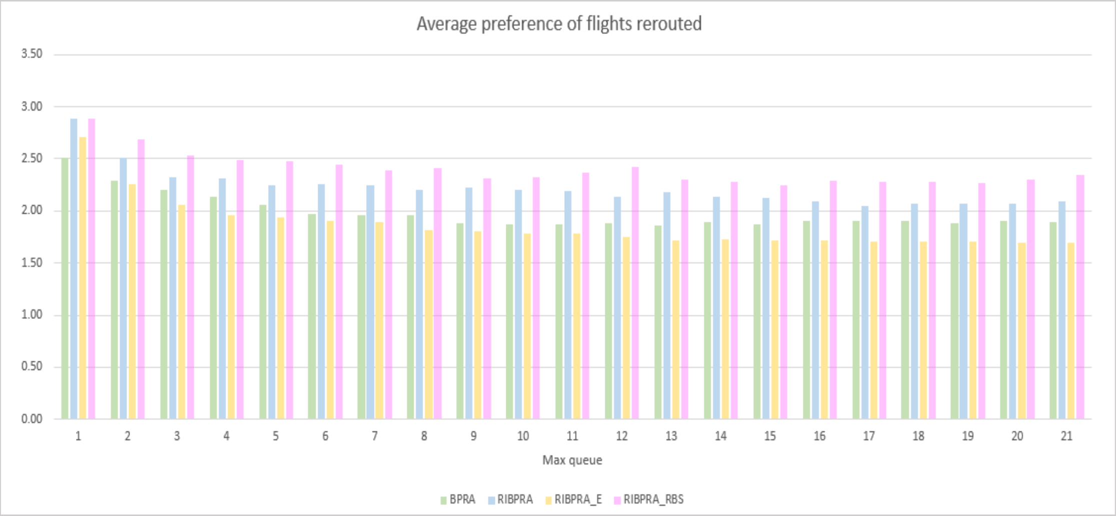


Figure 62: Average preference of rerouted flights by max queue

Chapter 8: Conclusion and Future work

CTOP is the logical progression of GDP and AFP operating in the CDM. It was developed by the FAA to combine the capabilities of a GDP and AFP. The advantages of CTOP over the traditional TMIs like GDP, GS, and AFPs are unequivocal. There have been concerns from the flight operators/airlines about its implementation, and the justification for investments in IT infrastructure required, as there have not been enough instances where the FAA has used a CTOP to manage the traffic imbalance. Fear of lack of participation from the airlines/flight operators and uncertainty about their responses has delayed the FAA from implementing CTOP. These differences between the FAA and airlines have led to very few instances where CTOP has been used. The concerns about allocation scheme used in the CTOP adds to the hesitation from the flight operators/airlines.

In our test case scenario, we exclusively looked at a situation where the nominal capacity of the airspace was reduced by fifty percent, and a single FCA was used. The reduced capacity forces the FAA to handle the demand and capacity imbalance situation by initiating a TMI, CTOP. CTOP not only assigns the required ground delay to flights but also reroutes to balance the demand and capacity. This research was motivated by the high ground delays that were experienced by flights and how the rerouting decisions were made in the current allocation method used in a CTOP. The flights experienced these high delay values because of a pseudo queue that developed due to factoring the adjusted cost value of route options from a TOS of a flight in the rerouting decisions. Whenever there is situation where a resource becomes constrained, there is bound to be competition among the participants (airlines/flight operators) vying for the constrained resource. Misleading information from the flight operators about its flights' RTC and TOS to make sure its flights were not rerouted would result in flight operators degrading the system performance, both the performance of the other participants and the respective flight operator's performance. The TOS and RTC information from the flight operators likewise did not completely express which were the flights that they would prefer to be rerouted, and which they want would not want to be rerouted.

Traffic management actions based on optimization models are the biggest form of uncertainty for the flight operators after uncertainties in capacity and demand due to weather forecasts. There has been extensive literature, and numerous optimization models that have been proposed historically aimed at achieving system efficiency. Although optimization models have been aided by the increased computational speed as a result of latest advancements in computing processor power, they represent a black box mechanism. These optimization models lack a key criterion to the collaborative routing problem, predictability. Predictability is transparency in the procedures employed by traffic managers (Hoffman et al., 2005). In a collaborative operating environment (CDM) dynamically changing traffic management practices and allocation procedures pose huge difficulties for flight operators to respond to changing conditions. These include uncertainties in information regarding the routes available, which aircraft will be rerouted by traffic managers, and when they will be rerouted.

We proposed four alternative approaches based on the idea that by ensuring a Q_max, which meant rerouting a small percentage of flights based on the preference value received from the flight operators, therefore not merely reduces an individual flight operator's delay but also the total delay incurred to the system. We also developed a model to assign the preference value of a flight, along with four different strategies that an airline/flight operator could employ to assign the preference values.

The proposed allocation methods, BPRA, RIBPRA, RIBPRA_E and RIBPRA_RBS, performed significantly better than the CTOP_RBS. We tried capturing the cancellations and substitutions, and compression processes within the framework of RIBPRA and RIBPRA_E. Although the results from RIBPRA and RIBPRA_E provided few indications we did not however prove it has the equivalent effect. We leave this as part of a potential future research work.

It is essential to note that CTOP can incorporate multiple FCAs within its framework and was built to handle multiple FCAs. Multiple FCAs are usually consecutive FCAs or sub FCAs of a large FCA. Although our test case scenario considers only a single FCA case, we hope the proposed allocation methods could be adopted to handle multiple FCAs and leave this discussion for future research.

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